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Self assembly of complex structures

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Self Assembly of Complex Structures

by

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ABSTRACT

The state of the art in artificial micro self assembly concepts are reviewed. The history of assembly is presented with a comparison to macro assembly, which has been widely studied, and micro self assembly. Criteria were developed and tested to show that macro assembly is more complex in ways that micro self assembly is not. Self assembly requirements for successful and complex self assembly, which evolved from the macro and micro comparison, are also established and tested. A method to assemble complex structures in the micro scale is proposed and demonstrated at the meso scale. The basic concepts of self assembly and a novel approach to complex multi layer self assembly is analyzed.

Chapter 1- Introduction

1.1 Thesis Statement

This thesis shows that the capabilities and processes of self assembly can be used to assemble complex systems on the micro scale effectively and efficiently. These techniques are promising for applications from the millimeter to the micrometer scale. First, a comparison of microscale self assembly and macroscale assembly is presented. Criteria are then developed to show the major differences in assembly capability between the two size scales. Next, experimental implementations of a more capable self assembly method, then previously reported, are presented and potential applications discussed. It is used to demonstrate assembly of a complex multi-layer structure significantly more complicated than previously reported artificial self-assembly systems.

1.2 Background

1.2.1 Assembly- Definition

The putting together of parts to make a finished product is the definition of assembly (Hounshell). Assembly, as defined in *Mechanical Assemblies* (Whitney 517), is a chain of coordinate frames on parts designed to achieve certain dimensional relationships, called key characteristics, between some of the parts or between features on those parts. Coordinate frames describe the position and orientation of a body in space. Matrix transforms developed from the coordinate frames of parts in assemblies are used to define the rotation and displacement of each part from each other. Key characteristics

(KCs) are geometric relationships between features on non-adjacent parts. Key characteristics are the assembly characteristics that need close attention because they are critical for performance, safety, and regulations. Chains, which are made up of physical elements, the associated organizations, and the capability of the processes, deliver the KCs. The parts simply provide material from which the assembly features can be fabricated so as to embody the desired constraint actions of the frames. This manuscript is going to use the concepts in Whitney's book to compare macro and micro assembly as a whole.

1.2.2 Assembly Manufacturing History

The object of assembly is to form a part of higher complexity with specified functions from the individual parts. Assembly and manufacturing until recently has been completed mainly by human hands. Manufacturing in Latin means "to make with hands". Human hands can make very detailed pieces, however it is very difficult for a human to manufacture the same exact piece repeatedly. For this reason, assembly would often become difficult due to the variations of each piece in the assembly. Each part in the early times of history was finished by a craftsman or team of craftsmen. This made it necessary for a craftsman to be an expert in all the various aspects of manufacture and assembly, thus making training a new craftsman a long and expensive task. Production was hindered by the limited availability of skilled craftsmen. This was called the English System of Manufacturing (Hounshell).

Honore le Blanc in France in the mid 18th century helped solve some of the issues of repeatability of parts by using templates. The templates allowed human-run machines to manufacture almost identical parts. The process of using templates was made famous by Eli Whitney in the early 19th century. War production needs motivated widespread adoption of interchangeable parts. Eli Whitney applied the template concept to gun making which allowed every barrel of a certain type of gun to be assembled to any stock of the same type of gun. His work brought about three primary developments in manufacturing methods. First, parts were manufactured on machines, resulting in higher quality than that of handmade parts. The parts were interchangeable resulting in simplified assembly. Second, the accuracy of the final product could be maintained at a higher standard. Third, production rates could be significantly increased. This process came to be known as the American System of Manufacturing and spread worldwide rapidly (Hounshell).

Looking at assembly manufacturing from the point of view of efficiency was the next major step in improving assembly. Scientific Management was developed by Frederick Winslow Taylor which consists of figuring out the cheapest, fastest, and most accurate way of carrying out each manufacturing process (Kanigel 688). Frank Gilbreth used photographs to show wasted worker motions and design more efficient motions. This was not widely accepted because the workers felt like machines. Taylor and Gilbreth were the people who developed the idea of waste elimination.

The automotive industry dominated new developments in assembly manufacturing during the 20th century. Henry Ford is recognized as the main contributor to the development of modern production and assembly methods (Collier and Horowitz). The assembly line he developed was applied to the automobile Ford Model T. Ford got the idea of the assembly line from William C. Klann upon his return from a slaughter house where they had a cutting line where each worker only removed one specific piece of cow and was very efficient. This allowed the total time of assembly to be reduced from 12 hours and 28 minutes to being able to produce 1 car every 10 seconds of the working day. The modern automated assembly line incorporates robots into the manufacturing process.

1.2.3 Assembly Methods

Industrial assembly methods can be divided into three major groups. In manual assembly, parts are transferred to workbenches where workers manually assemble the product or components of a product. Hand tools are generally used to aid the workers. Although this is the most flexible and adaptable of assembly methods, there is usually an upper limit to the production volume, and labor costs (including benefits, cases of workers compensation due to injury, overhead for maintaining a clean, healthy environment, etc.) are higher (Chan and Salustri).

Fixed or hard automation is characterized by custom-built machinery that assembles one and only one specific product. Obviously, this type of machinery requires a large capital investment. As production volume increases, the fraction of the capital investment compared to the total manufacturing cost decreases. Indexing tables, parts feeders, and automatic controls typify this inherently rigid assembly method. Sometimes, this kind of assembly is called "Detroit-type" assembly.

Soft automation or robotic assembly incorporates the use of robotic assembly systems. This can take the form of a single robot, or a multi-station robotic assembly cell with all activities simultaneously controlled and coordinated by a programmable logic controller or computer. Although this type of assembly method can also have large capital costs, its flexibility often helps offset the expense across many different products (Chan and Salustri).

The assembly methods listed above were invented because of the need for increased production and quality of products. Once demand increased, skilled laborers were not able to keep pace, thus creating a demand for new ways to assemble products faster by using custom built machinery. Each of the assembly methods has been developed to accommodate the changing production demands of new products and systems. Today, as the physical dimensions of many manufactured systems decrease and their complexity increases, new assembly methods are required. Robotic assembly is limited in the micro and nano scale ranges because of the forces needed to release the part from the grasp of the robot are too large and hard to manipulate parts at the micro scale. This leads to the concept of self assembly in the micro and nano scale range to aid in the production of microsystems and nanosystems.

1.2.4 Self Assembly

Self assembly is a process where separated or linked components spontaneously form ordered aggregates. The aggregates are formed because everything moves spontaneously to a minimum energy state. In self assembly, the parts are at lower energy levels when joined than when separated. This process occurs with components of the molecular and mesoscopic size. It is important in many fields: including chemistry, physics, biology, materials science, nanoscience, and manufacturing. Self assembly processes are a common occurrence in nature and technology. They involve components from the molecular (crystals) to the planetary scale (weather systems) and many different types of interactions.

There are many reasons for further research into self assembly. First, humans are attracted by the appearance of order from disorder. Second, living cells self-assemble, and understanding life will therefore require understanding self assembly. The cell also offers countless examples of functional self-assembly that stimulate the design of non-living systems (Ball ; Philp and Stoddart 1154-1196). Third, self-assembly is one of the few practical strategies for making ensembles of nanostructures. It will therefore be an essential part of nanotechnology. Fourth, manufacturing and robotics will benefit from applications of self-assembly. Fifth, self-assembly is common to many dynamic, multi-component systems, from smart materials and self-healing structures to netted sensors and computer networks. Finally, the focus on spontaneous development of patterns bridges the study of distinct components and the study of systems with many interacting components (Whitesides and Grzybowski 2418-2421).

Molecular self assembly is controlled mainly by physics and chemistry. Self assembly occurs when molecules interact with one another through a balance of attractive and repulsive forces. There are five characteristics that determine the success of self assembly in a molecular system (Whitesides and Boncheva 4769-4774).

1. Components- A self assembling system contains a group of molecules or a macromolecule that interact with one another. The interaction process leads to a final state which is more complex and ordered than less ordered initial state.

2. Interactions- Self assembly occurs when molecules interact with one another through a balance of attractive and repulsive forces. The Van der Waals bonds are weak which is appropriate for self assembly.
3. Reversibility- For self assembly to generate ordered structures, the association must be reversible or allow the components to adjust their positions once they have formed. The strength of the bonds must be comparable to the forces tending to disrupt them.
4. Environment- The self assembly of molecules normally is carried out in a solution to allow for the motion of components. The interaction of the components with their environment can strongly influence the course of the process.
5. Mass Transport and Agitation- The molecules need to be mobile for self assembly to occur. At the molecular scale, thermal motion provides the major part of the motion required to bring the molecules into contact. At larger scales, mixing and vibrational forces may be necessary.

It is possible to select among many interactions in non-molecular self-assembly. Possible interactions include Van der Waals, steric, entropic, ionic, magnetic, gravitational, and electrostatic. Table 1 shows the forces that are most significant on the micro scale for assembly. It is easier to fabricate non-molecular components than it is to produce molecules and observe the processes and products of the larger size components (Whitesides and Boncheva 4769-4774).

Table 1- Forces of Significant Magnitude in the Micron to Millimeter Scale.

Gravitational	Electrostatic
Magnetic	Capillary
Fluid Shear	Hydrodynamic
Hydrophobic	Van der Waals
Biospecific	Centrifugal

1.2.5 Static Self Assembly

Static and dynamic are the two main types of self assembly proposed by Whitesides (Whitesides and Grzybowski 2418-2421). Static assembly involves systems that are at global or local equilibrium and do not dissipate energy. For example, molecular crystals (Isaacs, L. , Chin, D. N. , Bowden, N. , Xia, Y. & Whitesides, G. M.) are formed by static self assembly; so are most folded, globular proteins. In static self assembly, formation of the ordered structure may require energy for example in the form of stirring, but once it is formed, it is stable. The study of static self assembly is particularly relevant as an alternative technique for MEMS fabrication. Most research in self assembly has focused on this static type.

1.2.6 Dynamic Self Assembly

In dynamic self assembly the interactions responsible for the formation of structures or patterns between components only occur if the system is dissipating energy. The patterns that are formed by competition between reaction and diffusion in oscillating chemical reactions (Aizenberg, Black and Whitesides 495-498; Hess 199) are simple examples; biological cells are much more complex ones. The study of dynamic self assembly is in its infancy.

1.3 Self Assembly Literature Review

1.3.1 Molecular Self Assembly

Molecular self assembly is the assembly of molecules without guidance or management from an outside source. The construction of molecular crystals, lipid bilayers, and phase separated polymers, and self assembled monolayers are all examples of molecular self assembly. Molecular self assembly is seen in the formation of double helical DNA through hydrogen bonding of the individual strands and in the assembly of proteins to form quaternary structures.

Covalent bonding, which is the primary chemical bond, serves as an interaction in the self assembly of molecules and nanoclusters. Netzer and Sagiv were the first to introduce chemical self assembly, which is based on chemisorption of monomers, polymers and semiconducting and metallic moieties onto specific substrates (Netzer and Sagiv 674). Since then many groups have been able to obtain mono-layer protected clusters using mercapto-alcohols, mercaptocarboxylic acids and thiophenols on gold, silver, CdS, ZnS, and CdSe.

Sarathy demonstrated layer by layer fabrication of nanoparticle-moleculer spacer sandwich-type structure into superlattices using dithiols, metal, and semiconducting nanoparticles (Sarathy et al. 399).

Multiple research groups have developed procedures to utilize proteins, DNA oligomers, and other biomolecules for self assembly. Biological systems are characterized by complex structures, yet the assembly is dictated by highly selective, non-covalent interactions, such as hydrogen bonding and Van der Waals attractions (Huie 264-271). Mirkin has established processes for the formation of aggregate metal nanoclusters using DNA as a recognition element (Mirkin et al. 607-609). Mirkin's group used two different sets of 13 nanometer gold nanoparticles bound to non-complimentary DNA ogligonucleotides capped with thiol groups. The final structure of gold can be reversibly annealed to disassemble the colloidal network.

Protein molecules have contributed as self assembly promoters. Yamashita demonstrated a two dimensional array of iron-oxide nanoparticles, which was realized using ferritin supramolecules as scaffolds (Yamashita 12-18). Iron oxide loaded ferritin molecules self assembled at the air/water interface, which were transferred to a silicon substrate. Heat treatment was then applied to remove protein shells leaving a close-packed arrangement of inorganic nanoparticles. Biological molecules as self assembly promoters allow systematic understanding and fabrication of complex yet functional structures at the molecular level.

1.3.2 Micro Self Assembly

Microassembly has had various approaches proposed to fabricate and assemble microdevices onto substrates. These approaches include selective area growth, where devices are grown directly onto a silicon substrate, flip-chip bonding, which is used to connect integrated circuits to printed circuits and packages, electrostatic assembly, fluidic self assembly, and magnetic assisted assembly. Each of the previously mentioned approaches has advantages and drawbacks. The development of these approaches were established because of the force, speed, and cost constraints of pick and place serial assembly in smaller scales. Micro self assembly is studied in this thesis because of the low cost and ease of assembly using self assembly.

Assembly rates increase as the size of the parts decreases from meters to millimeters. This occurs because inertia has a less significant role at smaller scales and most of the systems at the smaller scales require less complex assembly geometries. Figure 1 shows the approximate speed versus approximate range of part size for a variety of serial assembly methods.

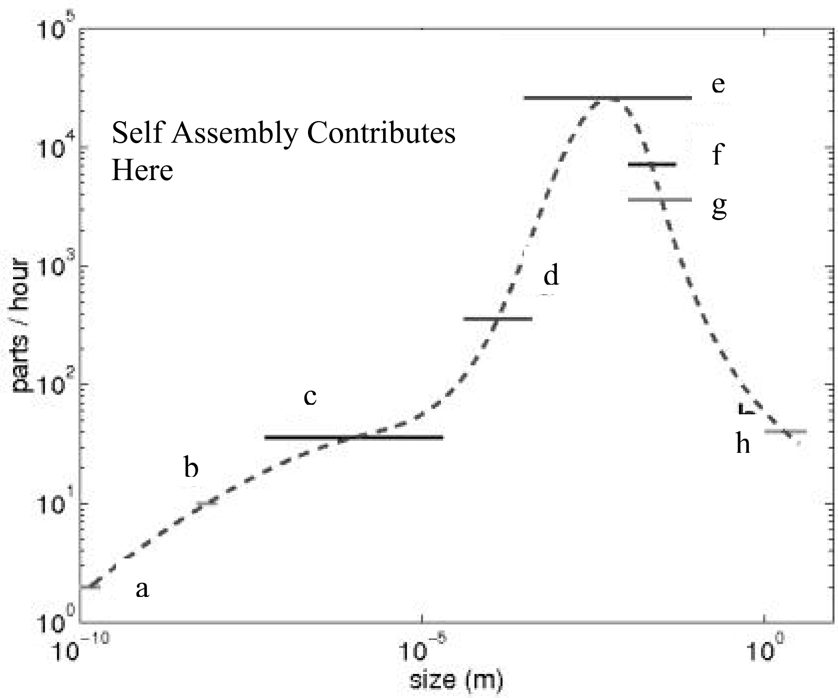


Figure 1- Speed Versus Range of Part Size for a Variety of Serial Assembly Methods. The enclosed zone specifies where self assembly can contribute. (Morris 600-611)

The peak of the curve in Figure 1 shows the state-of-the-art for pick and place assembly. As the size of the components head towards the nano scale, the assembly rate decreases. This occurs because it is difficult to grasp, handle, and position small components correctly. Current microassembly capability is trapped between high equipment cost and limitations on speed of serial processes done by pick and place robots. The current difficulty of assembly in the small scale ranges is motivation to find other ways to assemble in those ranges, thus introducing self assembly as a solution to the problem.

1.3.3 Driving Forces of Self Assembly

With components at the molecular scale and larger than molecules, there are many interactions (Van der Waals, capillary, ionic, steric, entropic, magnetic, gravitational, electrostatic, and more) that can be used. The many possibilities of interactions allow for a more flexible design strategy.

Capillary interactions are abundant in microscale self assemblies. Since capillary forces are proportional to the length of the solid-liquid interface, they become dominant over all other forces at the microscale. Capillarity is the tendency for interfaces involving fluids to minimize their areas which results in self assembly of components. The interactions are highly flexible: they can be adapted, can be modeled easily, can be used for 2D and 3D structures, and the force or strength of bond can be changed without difficulty. In previous studies, the liquids most commonly used and cited are molten solder and adhesives. The liquid solder causes the components to assemble to the substrate and provides electrical connections when needed.

Whitesides and his group members were among the first to use capillary interactions in mesoscale self assembly. Whitesides et al. used hydrophobic and hydrophilic surfaces to demonstrate 2D self assembly (Wu, Bowden and Whitesides 3222-3224). The same group also coated selected faces of 3D components with a film of low melting point solder. Upon agitation by hand, the objects collide and interact through capillary forces between the drops of the liquid alloy (Breen et al. 948-951).

Zheng and Jacobs also used capillary forces; however they also included shape recognition in their demonstrations. The group was able to create microsystems by sequentially adding different types of components to the assembly solution (Zheng, Buhlmann and Jacobs 12814-12817). The shape recognition was achieved by having one whole side of the light emitting diode (LED) coated with gold and the opposite side coated with a small circle of gold. If the small circle would try to attach to the solder, it would fail because the capillary force was not enough to hold the LED in place. The solder provides both the driving force for assembly and the electrical and mechanical connections. This system was used to create assemblies of 3 parts that serve to encapsulate a functional component.

Gravity, which is a much weaker force than capillary forces at the microscale, has been used as a driving force in fluidic self assembly (Morris, Stauth and Parviz 600-611). Components are agitated to move across the substrate until they fall into recesses or wells. Once the parts are in the recesses, Van der Waals and capillary forces act on the parts to aid in assembly on the substrates. Singh used gravity to assemble optoelectronic devices. Singh showed the ability to assemble 100 multiple-sizes laser diodes on silicon wafers with 100% efficiency at high speed and accuracy of less than 2 μm (Singh et al. 176). Gravitational based assembly methods have demonstrated the highest assembly rate.

1.3.4 Control of Self Assembly

All types of assembly require control to allow for correct alignment and assembly. Control allows the creation of more than one assembly from a given set of parts. Fixtures that orient certain parts correctly and templates that ensure alignment are used for control. The use of fixtures requires the ability to place and remove parts on and off the fixture. This requires a reversibility of the bonds, which in self assembly, can be achieved through molten solder connections and soluble adhesives. This can be achieved by physical fixtures or alignment pedestals, electric fields, magnetic fields, or changing surface properties of substrates.

The ability to control assembly sequence is also very important. If the parts are not assembled in the correct order, the final product will not work. For example, if the parts of an assembly are in a bag and each part is pulled out at random, assembly could not be achieved because of the out of order sequence of the parts. Groups have been able to control assembly sequence while using self assembly by adding one part type at a time and then adding subsequent part types until full assembly is achieved.

O'Riordan et al demonstrated programmable spatial control over object position using electrostatic forces (O'Riordan et al. 467-471; O'Riordan, Delaney and Redmond 761-765). In their field assisted device transport and trapping method, electric fields drive the transport, positioning, and trapping of devices at each selected receptor site.

Chung et al achieved programmable, reconfigurable assembly by embedding small heaters to locally melt solder pads and enable component bonding to the pads (Chung et al. 457-464). The group was able to turn "ON" the substrates by powering the heater to melt the solder. When the heater is turned off, the solder freezes and holds its state. This can be used to assemble different part types and control sequence. However, because the heaters and circuits were in the parts themselves, the cost and difficulty of manufacturing increased. Figure 2 shows the parts, the substrate with the heaters, and the concept to activate certain receptor sites. Errors that were seen from this method were unoccupied binding sites and two parts on one binding site.

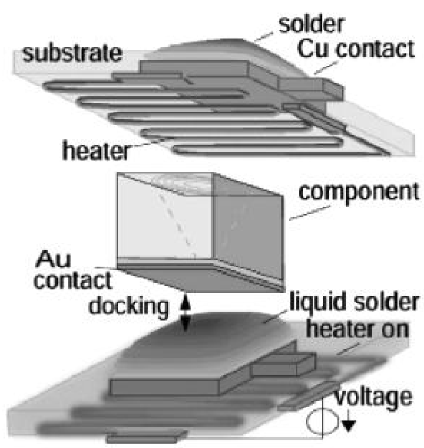


Figure 2- Structure of Substrate with Heater Embedded. Solder sites are programmed by applying external voltage to embedded heaters. (Chung et al. 457-464)

Xiong et al created a surface with electrochemically switchable surface properties called self assembled monolayers (Xiong et al. 117-127). The group was able to develop a hydrophobic layer on the gold binding sites that yielded a contact angle of 110°. Assembly is controlled to take place on desired binding sites by using an electrochemical method to deactivate specific substrate binding sites. By repeating this process, different batches of micro sized parts can be consecutively assembled on a single substrate. The primary drawback to this technique is the deactivating of binding sites takes over two hours.

1.4 Thesis Outline

The thesis proceeds as described next. Chapter 2 develops criteria for comparing assembly complexity across size scales. These criteria are used to compare macro assembly to micro self assembly and show how micro self assembly has limited complexity. Chapter 3 presents criteria for successful self assembly processes of complex structures and evaluates the self assembly process studied in this project for self-assembly of complex structures. This method is applied to the self-assembly of a simulated thermoelectric cooler. Chapter 4 reviews the important achievements of the work and recommends future areas of study.

Chapter 2- Comparison of Macroscale Assembly and Microscale Self Assembly

The goal of this thesis is to show that micro assembly has limited capability compared to macro assembly and to demonstrate an approach using self assembly to create more complex assemblies at the micro scale. This chapter discusses the similarities and differences in assembly at the macro and micro scales. Criteria to compare the different scale assemblies are presented and studied. A case study is also presented to show the systematic differences between macro assemblies and current micro self assembly capabilities.

2.1 Key Characteristics and Liason Diagrams

Typical macro assemblies consist of many parts, each with a few important geometric features, all of which must work together in order to create the product's several functions. These important features are referred to as key characteristics. Key characteristics (KCs) were adopted to focus attention on those dimensions that were critical, affected a variation-sensitive characteristic, and were worth controlling. KCs are the product, subassembly, part, and process features whose variation from nominal significantly impacts the final cost, performance, or safety of a product (Thornton 145-157).

Much can be learned about an assembly by studying the connections between its parts. Whitney proposed a method of abstractly representing these connections through liason diagrams which will be used in this thesis (Whitney 517).

This diagram replaces the parts with dots and connections between parts with lines. Each liason represents a place where two parts touch. Such places are called assembly features. They serve to position the parts with respect to each other.

A desktop stapler, from *Mechanical Assemblies*, is studied to show the concept of a liason diagram and key characteristics (Whitney 517). Figure 3 shows the stapler structure and the main parts: the base, the anvil, the carrier, and the handle.

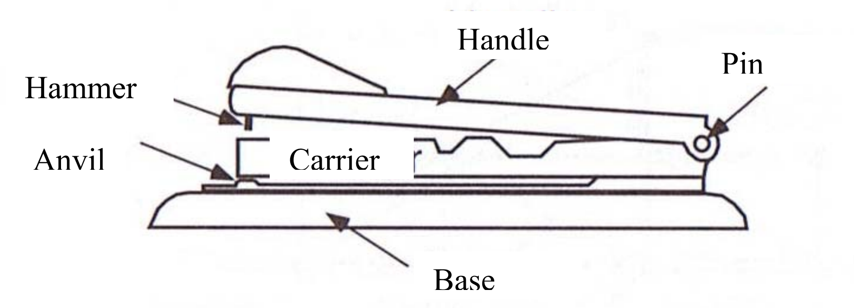


Figure 3- Structure of Stapler. Shows main parts of stapler: base, anvil, carrier, and handle. (Whitney 517)

Each part (shown as dots) and connections (shown as lines) are displayed in Figure 4 to create the liason diagram for the stapler. Some features act to hold a part firmly against another, while other features allow some relative movement between the parts. The liason between the rivet, base, and anvil fixes these parts to each other completely, while the liason between the anvil, pin, and handle allows the handle to rotate with respect to the anvil.

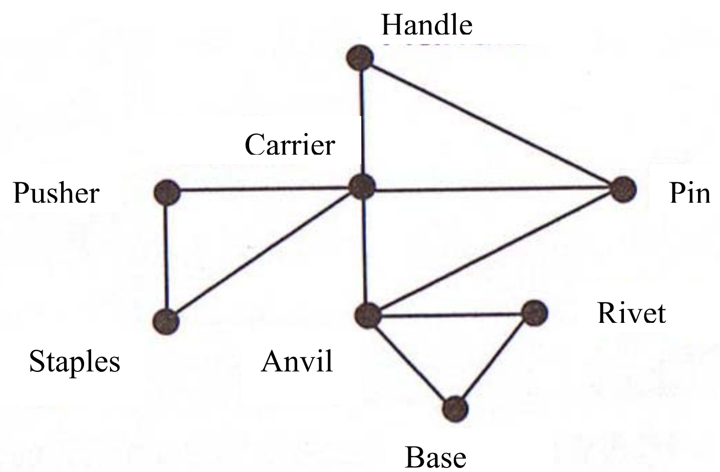


Figure 4- Liason Diagram for Stapler. (Whitney 517)

The important dimensional relationships between the parts at either end of each line pair are called key characteristics. If the relationships are right, the product will work; if not, then it will not. Key characteristics can be represented on a liaison diagram as double lines between the parts whose spatial relationship must be managed. Figure 5 shows the liason diagram of the stapler with key characteristics added. The assembly features play the crucial role of positioning the parts properly with respect to each other so that the key characteristics can be achieved accurately. That is, not only must each part have the correct dimension, but they must be assembled to accurately and repeatably.

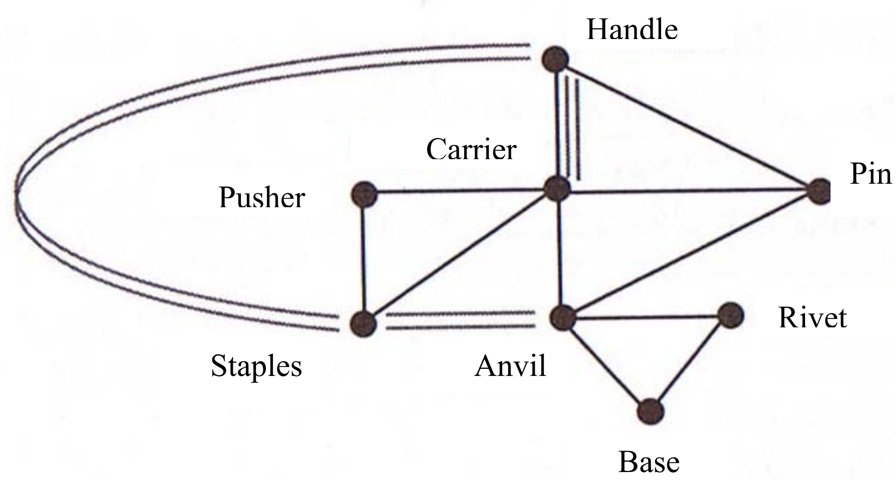


Figure 5- Liason Diagram of Stapler with Key Characteristics Indicated by Double Lines. (Whitney 517)

In order for the stapler to work correctly, the carrier must position the staple right over the anvil's crimp area and the handle must position its hammer right over the staple so that it strikes it squarely. If any of the parts are assembled incorrectly, the stapler will malfunction.

2.2 Macroscale Assembly vs. Microscale Assembly

One of the main problems that has to be addressed at the micro scale is the effect of force scaling in the micro world, where inertial forces scale down much faster than adhesion forces, thus rendering the releasing phase of components more difficult than the grasping phase. Gravitational forces are proportional to object volume whereas adhesion forces are proportional to object surface, so that the latter become larger than the former when dimensions scale down. Figure 6 shows this relationship between forces and object size. Adhesion forces are the main problem at the micro scale, while gravitational forces are the main problem at the macro scale. The adhesion forces are: 1) Van der Waals forces, which are due to instantaneous polarization of atoms and molecules by quantum mechanical effects; 2) electrostatic forces, which arise from charge transfer during contact; and 3) surface tension forces, which originate from interactions of layers of adsorbed moisture on the two surfaces. Balance of these forces fully depends on environment conditions (humidity and temperature), contact surface conditions and on materials (Menciassi 311).

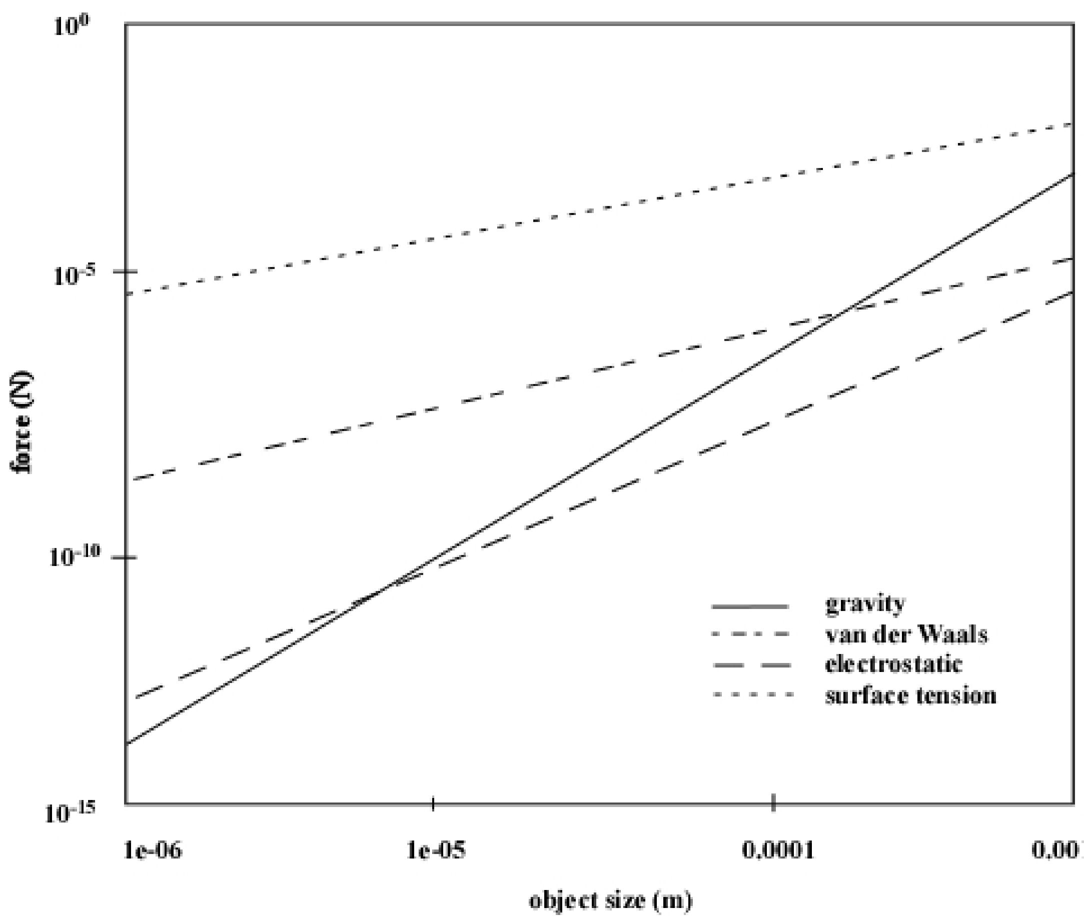


Figure 6- Force vs. Object Size. Plot is a log log scale. (Shet 451-470)

At macro scale robotic assembly, the manipulator and fixturing are purely mechanical, and force control can be used to reduce part damage and unwanted collisions of parts. Microscale robotic assembly is similar, but the parts must be fixtured or gripped at all times since gravity isn't preferred in the microscale to determine final position and orientation. Table 2 shows a comparison between assembly at the macroscale and microscale (Popa and Stephanou). It shows the challenges that need to be overcome at the micro scale be it part positioning, force control, or visual aids while looking at assemblies.

Table 2- Comparison Between Macroscale and Microscale Assembly for Different Assembly Attributes. (Popa and Stephanou)

Assembly Scale->	Macroscale	Microscale
Assembly Attribute		
Positioning	Easy	Difficult
Velocity	cm/s and m/s	Slow µm/s, or mm/s
Force Control	Easy, necessary to avoid part damage	Difficult, forces can be as low as µN
Dominant Forces	Gravity, Friction	Surface forces: Van der Waals, electrostatic, stiction
Throughput	Serial assembly provides adequate throughput	Parrallel assembly or self assembly is needed
Vision	Easy, can be seen with eyes	Difficult (equipment is expensive)
Fixturing	Mechanical	Micromechanical fixturing must be used

2.3 Criteria for Comparison

For the comparison of assemblies in the macro scale and micro scale, macro assembly is used as a standard. This comparison was done to show how more complex macro assembly is than current micro self assembly and why a new assembly process is needed to make complex assemblies in the micro scale. This thesis proposes a self assembly method capable of creating complex assemblies. Macro scale assembly is a mature field, has been studied thoroughly, and is well-understood. Macro scale assembly uses temporary connections to fixtures, has excellent sequence control, and can assemble many different parts while micro self assembly is very simple. Micro self assembly as it is now has very little if any programmable control, the assemblies being accomplished are very simple, reversible bonding of parts is limited, and the template or substrate can only be used once. While it is clear that current micro self-assembly systems appear less capable than macro assembly systems, it is desirable to develop metrics for comparison.

To show the comparison of micro assembly and macro assembly, criteria have been established to show the similarities and differences between the two that are independent of scale and assembly application. These criteria have been developed based on the liaison diagram representations of assemblies (Whitney 517) since these provide an abstract representation that is independent of assembly scale and application. The liason diagrams allow for easy identification of parts and connections. Four different criterion are proposed.

1. Part Variety- Defined as the number of part types divided by the total number of parts in the assembly. A higher value for part variety indicates a more complex assembly while a lower value indicates a simple assembly.

$$Part\,Variety = \frac{\#of\ Part\,Types}{Total\,\#of\ \ Parts}$$

2. Liasons per part- Defined as the number of liasons divided by the number of parts. The number of liasons per part allows us to normalize the amount of constraint among parts in many assemblies. This is the same as the network complexity factor in graph theory. The network complexity factor is defined as the ratio of the number of arcs in a network to the number of nodes. In this study, nodes are parts and arcs are liasons. For typical engineered products, the number of liasons per part hovers around the theoretical minimum, and none exceeds two.
3. Liason Index- Defined as the liason per part divided by the minimum liason per part. A liason is defined as the number of joints. Liason per part is the total number of liasons divided by the number of parts. The liasons per part wants to stay a low value because more liasons mean more toleranced interfaces, more complexity, more cost, and more places where failure could occur. Assembly is also easier if inserting a part requires paying attention to only a few joints with other parts. As liasons per part increases, the likelihood of over constraining the assembly is introduced. Over constraint makes the assembly performance much more sensitive to part variations. The minimum ratio of connections to nodes is the minimum liasons per part and is expressed by the equation:

$$\frac{MinLiasons}{Part} = \frac{n-1}{n}$$

The liason index equation is as follows:

$$Liason\,Index = \frac{\frac{Liasons}{Part}}{\frac{Min\,Liasons}{Part}}$$

4. Max Liason Chain Length- Defined as the maximum number of liasons in a chain. A higher value shows a more complex assembly. The minimum value for an assembly with more than two parts is two. The value is counted by following the liasons throughout the liason diagram until a part is repeated or the chain reaches a dead end.

2.4 Case Study of Micro Self Assembly vs. Macro Assembly

A case study to show how the criteria are applied is shown here. Assemblies from both size scales are chosen to show the differences. The micro self assembly case is LED's assembled on a substrate (Zheng and Jacobs 1387). Figure 7 shows a picture and liason diagram of the assembly. As can be seen from Figure 7, the assembly is very simple and only has three part types, however, multiple parts were needed to have full assembly. Zheng discovered that an excess of parts were needed in the assembly suspension to have complete assembly. The assembly was accomplished using 100 dies in 5 minutes. The part variety had a value of 0.03 because there were only three part types and the number of parts used for assembly was large. An accuracy of 0.3° and 19 µm of lateral accuracy were achieved. The max liason chain length is 2 because of the parts only being attached to the substrate in a single layer. The value would be higher if multilayered self assembly was done.

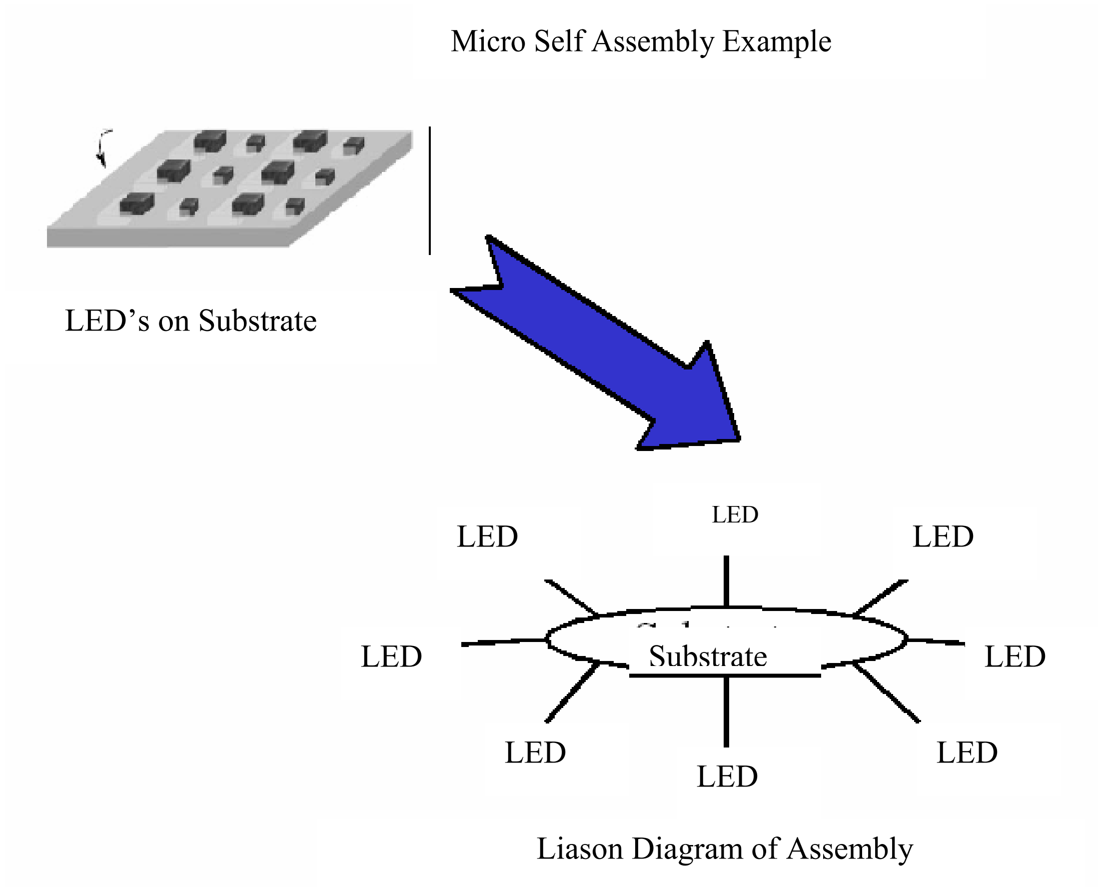


Figure 7- LED Assembly.

The macro assembly case is a juicer taken from *Mechanical Assemblies*. Figure 8 shows a picture of the juicer and the liason diagram of the juicer. The liason diagram shows that the max chain length is 7 starting from the transmission gear going to the squeezer. All of the parts of the final assembly are different, so the part variety is much greater than the micro self assembly case. The part variety has a value of 1 which is the maximum. A value of 1.13 for the criteria liasons/part is accomplished because some parts, like the transmission shaft, are attached to more than one other part, unlike in the micro self assembly case where each part is attached to a substrate.

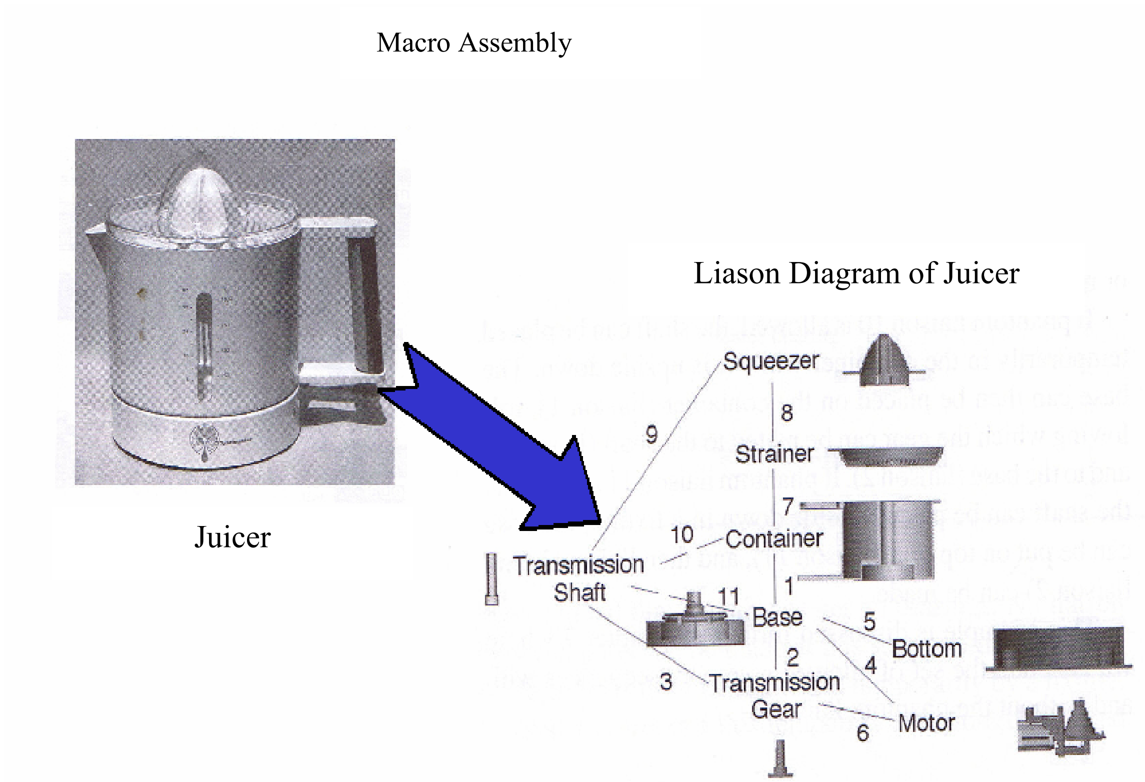


Figure 8- Macro Assembly of Juicer.

The case study clearly shows the difference in the two size scales. The juicer has values much greater than the LED assembly in part variety and max liason chain length. This leads to the conclusion that the macro assembly is more complex than the micro self assembly. Multiple assemblies in both size scales are presented later in this chapter in the form of tables and graphs to show the disparity between the size scales.

2.5 Criteria Application

The criterion developed above has been applied to macro assemblies presented in *Mechanical Assemblies* and to micro self assemblies from the literature. The tables and graphs below show the similarities and differences between assemblies at the two size scales which further show the differences in the size scales.

Table 3 shows the micro self assembly values. The journal papers used in the study represent the forefront of current work being done in micro self assembly. Part variety values are very low because of the limited part variety and excessive number of parts used in assembly. The values for max liason chain length are all at the minimum value except in one case.

Table 3- Micro Self Assembly.

Author	Micro Papers	Liasons/ Part	Liason Index	Max Liason Chain Length	Part Variety
Zheng	LED's on a substrate	1	1	2	0.003
Jacobs	LED's on cylindrical display	0.99	1	2	0.018
Grzybowski	Fluidic Machines	0.94	1	2	0.188
Gracias	3-d electrical network	1.17	1.27	12	0.083
Zheng	2 different sized LED's on substrate	0.99	1	2	0.020
Srinvisan	Microstructure to substrate/ square parts	0.98	1	2	0.020
Singh	Red and IR LED's on substrate	0.99	1	2	0.025
Fang	Micro component to substrate	1	1	2	0.001

Two examples of micro self assembly are shown in Figure 9 and Figure 10 to further demonstrate the data presented. The 3-D electrical network was assembled in a flask full of hot, isodense, aqueous KBr solution using manual agitation. This example was the only case in the micro self assembly cases that had a max chain length larger than two with a value of twelve.

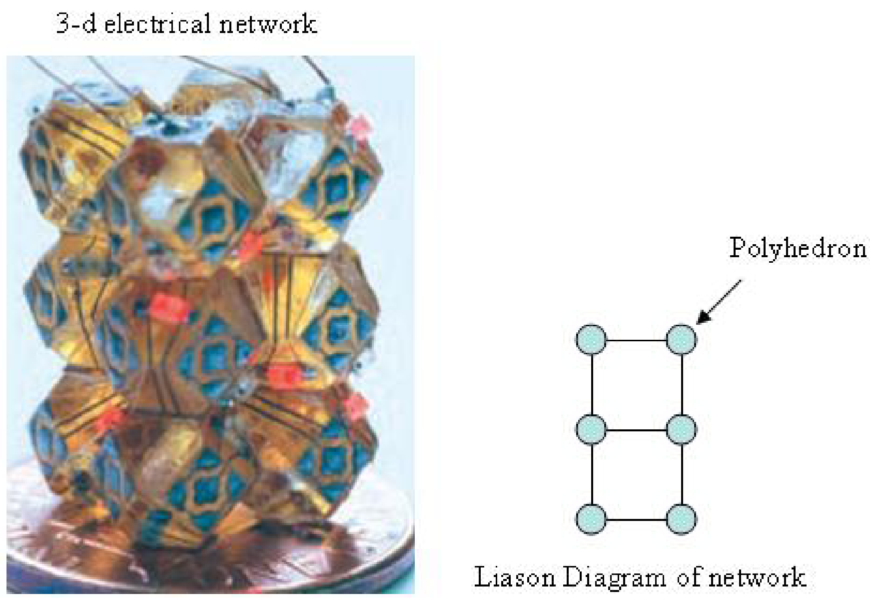


Figure 9- 3-D Electrical Network. Picture of network and liason diagram. (Gracias et al. 1170-1172)

Figure 10 shows the assembly of two different types of LEDs (IR and Red) on a substrate. The LEDs were assembled in two steps: first with coarse precision with a confinement mask to bring the LEDs near the recesses and then used fluidic and gravitational forces were used to finely position the LEDs (Singh et al. 345-351). This process gave 100% fill and accuracy of less than ± 2μm.

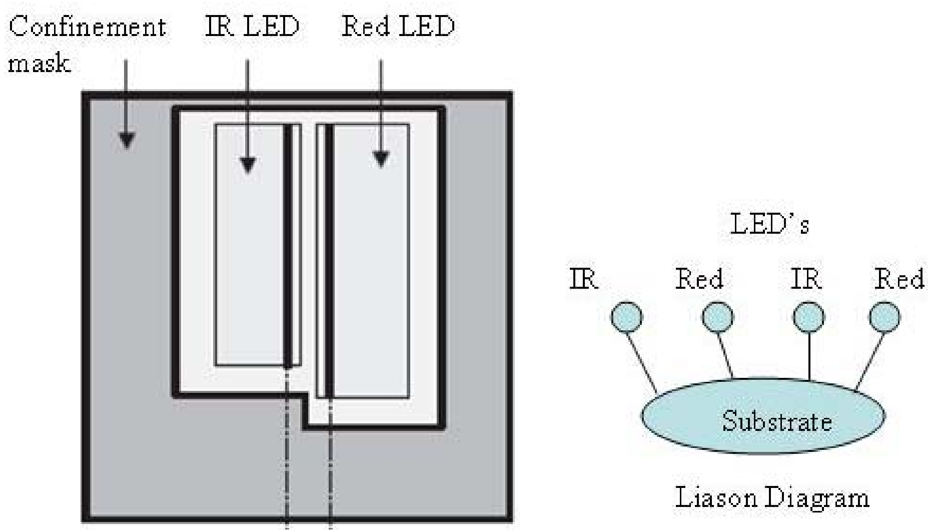


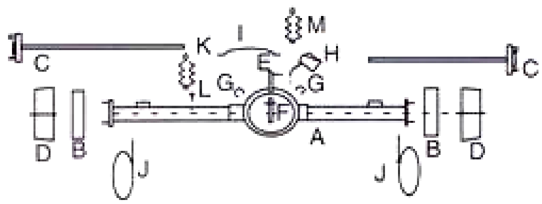
Figure 10- Two Different LED's Assembled on Substrate. (Singh et al. 345-351)

Table 4 shows the macro assembly values. All of the macro assemblies are taken from *Mechanical Assemblies* except the printed circuit board of an HP desktop printer. The printed circuit board has 136 parts, 28 part types, and 135 liasons. The assemblies presented are simple assemblies like a ballpoint pen and complex assemblies like a six speed transmission.

Table 4- Macro Assembly Examples.

		Liason Index		
Macro Comparisons	Liasons/Part	(Liason/part)/(min/part)	Max Liason Chain Length	Part Variety
Throttlebody	1.40	1.75	3	0.8
Ballpoint pen	0.83	1	5	1
Juicer	1.13	1.29	7	1
Rear Axle	0.92	1	3	1
Transaxle	1.67	1.88	5	1
6 speed transmission	1.64	1.8	7	1
Stapler	1.38	1.57	5	1
Small Fan Motor	1.25	1.67	2	1
Printed Circuit Board for Printer	0.99	1	2	0.22

Two examples are shown of the macro assemblies displaying a picture of the product and the liason diagram of each assembly. Figure 11 shows a picture and a liason diagram for a rear axle. The rear axle has 13 parts and 12 liasons. The max chain length is 3.



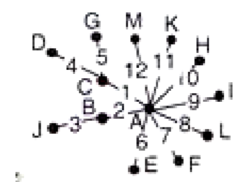
Parts of Rear Axle

Parts

A = Carrier Assy
B = Backing Plate
C = Shaft
D = Brake Drum and Nut
E = Pinion Shaft & Bolt Withdrawn
F = Pinion Shaft & Bolt Re-inserted
G = Push In Shaft & Insert C-Washer & Push Shaft Out
H = Oil
I = Cover
J = Brake Cable, Coiled
K = Final Press Test
L = Air Test Plug
M = First Pressure Test

Liaisons

1 = C to A
2 = B to A
3 = J to B
4 = D to C
5 = G to C
6 = E to A
7 = F to A
8 = L to A
9 = I to A
10 = H to A
11 = K to A
12 = M to A



Liason Diagram

Figure 11- Picture and Liason Diagram of Rear Axle Assembly. (Whitney 517)

Figure 12 shows a picture, schematic, and liason diagram of a throttle body. The throttle body is a much simpler assembly and can only be assembled in one sequence.

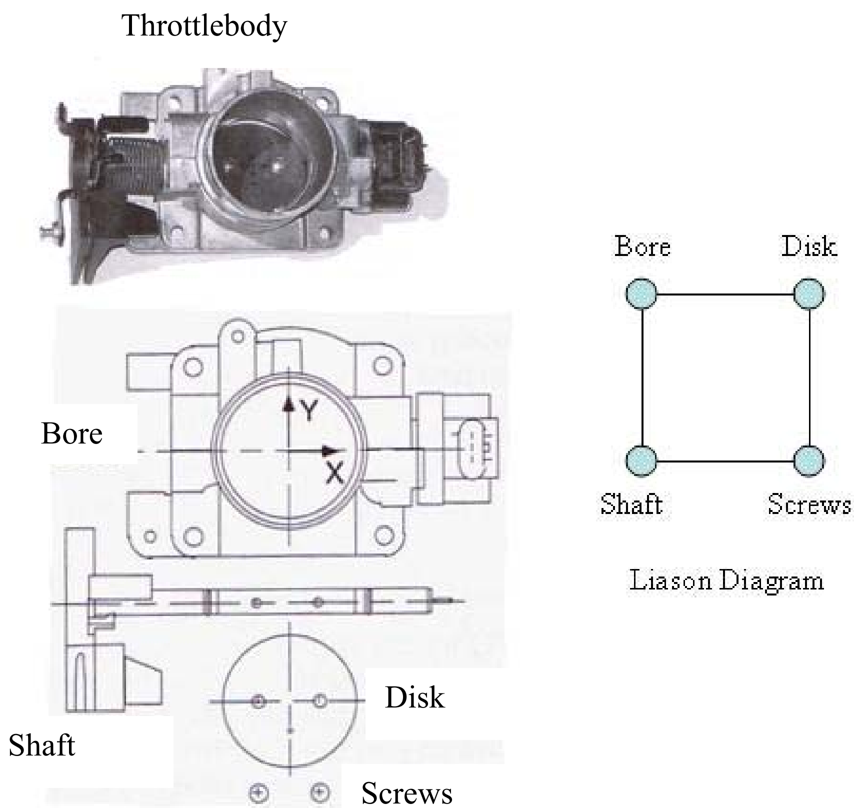


Figure 12- Picture, Schematic, and Liason Diagram of Throttle Body. (Whitney 517)

The following graphs use the data from the tables above to show the differences in macro assembly and micro self assembly using the developed criteria. The part variety seen in Figure 13 in micro self assembly is very minimal. A value of 1 is the maximum value for part variety.

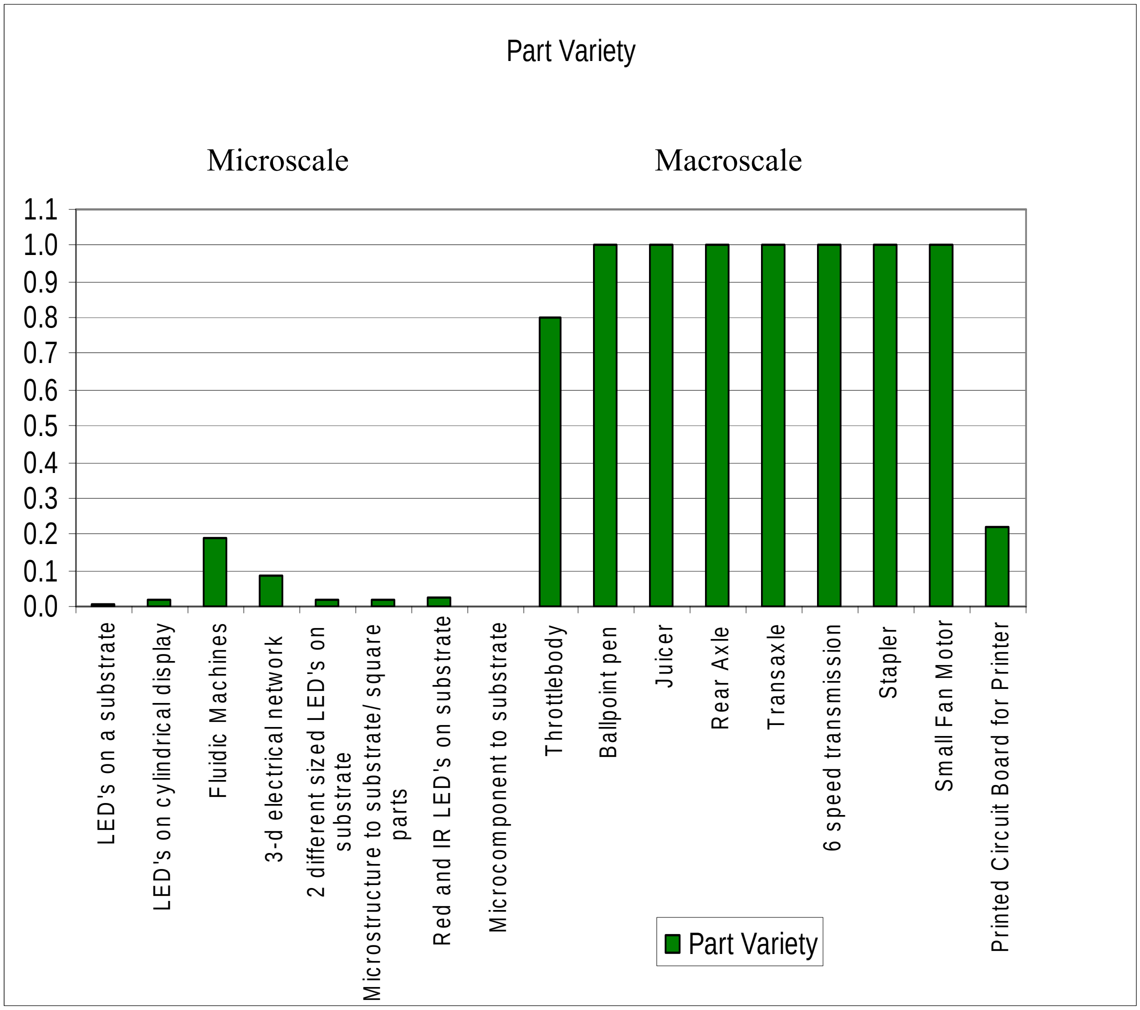


Figure 13- Part Variety.

The highest value in the micro scale is 0.1875, while the highest value is 1 in the macro scale. This criteria has the biggest difference between macro scale and micro scale. In many macro scale assemblies, each part is unique and there is only one case where a part is repeated. However, in the micro scale self assemblies, the parts are all mainly one type which allows for the label of a simple assembly. The part variety for micro scale self assembly is also very low because an excessive number of parts are needed to achieve complete assembly.

The liason index criteria do not have as large a difference between the size scales as part variety as shown in Figure 14. For typical engineered products, the liason index is near the theoretical minimum, which is 1, and none exceed 2.

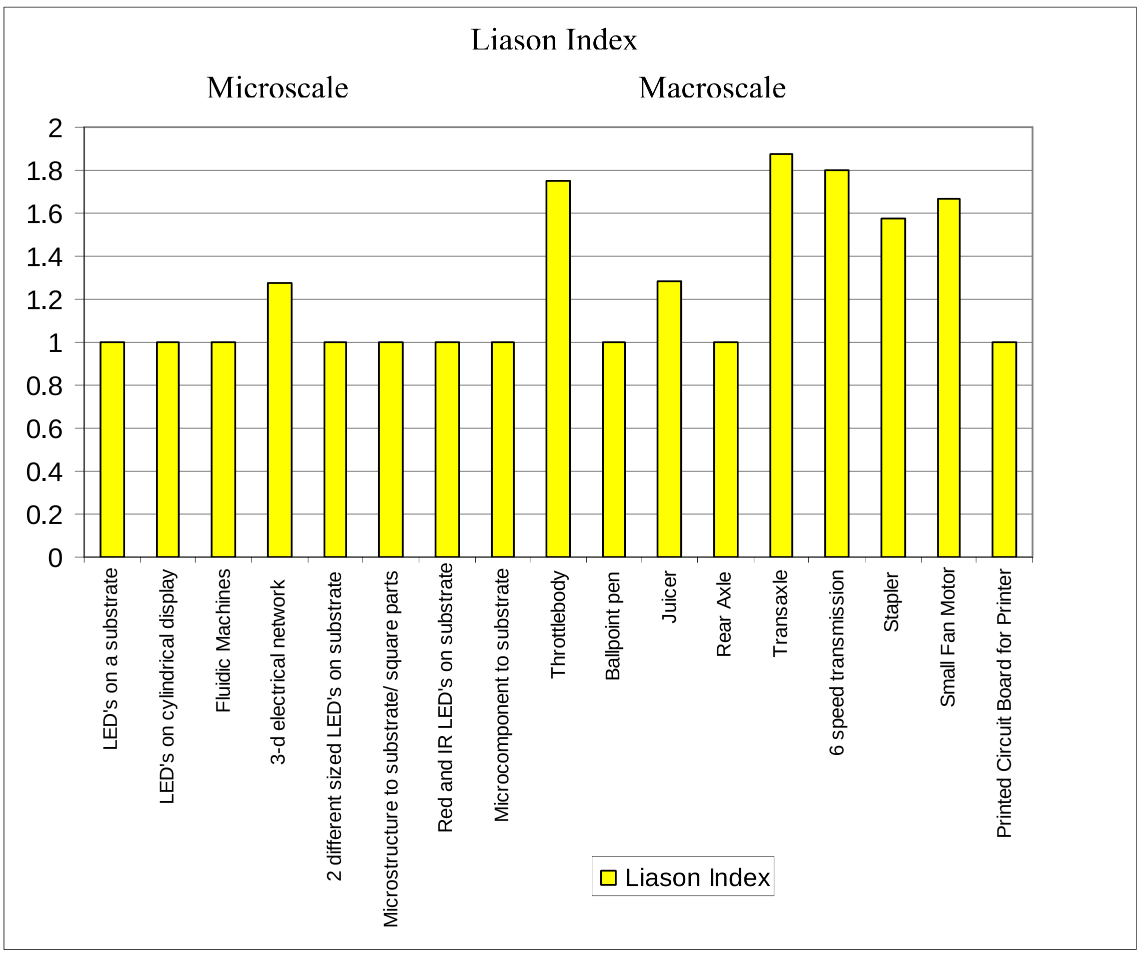


Figure 14- Liason Index.

If the liason index gets too large, over constraint can occur, thus affecting the possibility of having a correct assembly. As can be seen, none of the cases exceed 2, so assembly should occur without any error.

The max liason chain length graph in Figure 15 shows that micro self assembly is simple and has few steps in the assembly process.

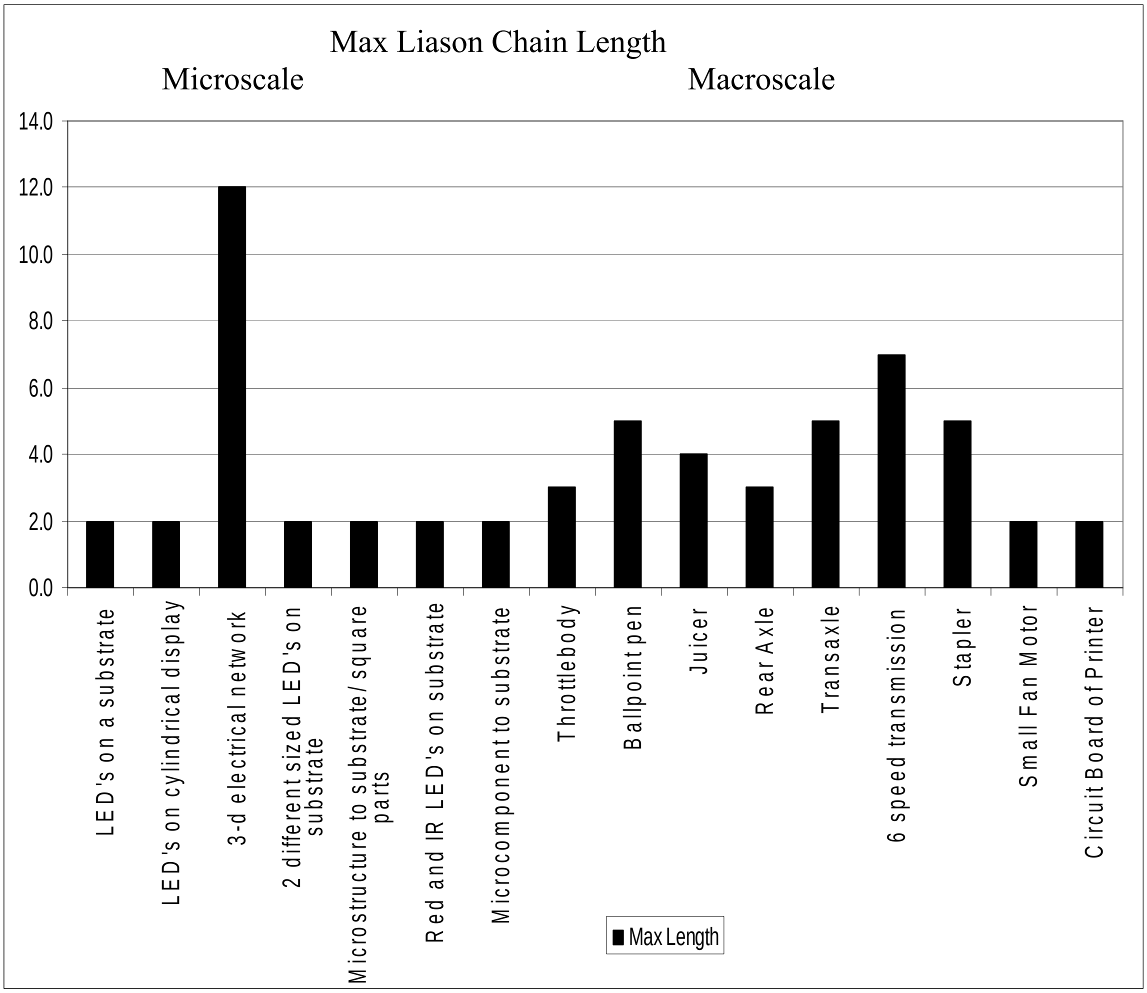


Figure 15- Max Liason Chain Length.

The only anomaly was the 3-d electrical network created by Gracias, which had every part attach to each other creating a large network (Gracias et al. 1170-1172). Every part in that case had the same dimensions and structure which allows for many parts to assemble to each other. Most of the micro self assembly work has a low chain length because most of the parts are being assembled to a single substrate with only one layer being assembled. Macro assembly cases show values greater than 2 allowing a designation of more complex assemblies.

The difference in Liasons/Part, shown in Figure 16, for macro assembly and micro self assembly is minimal.

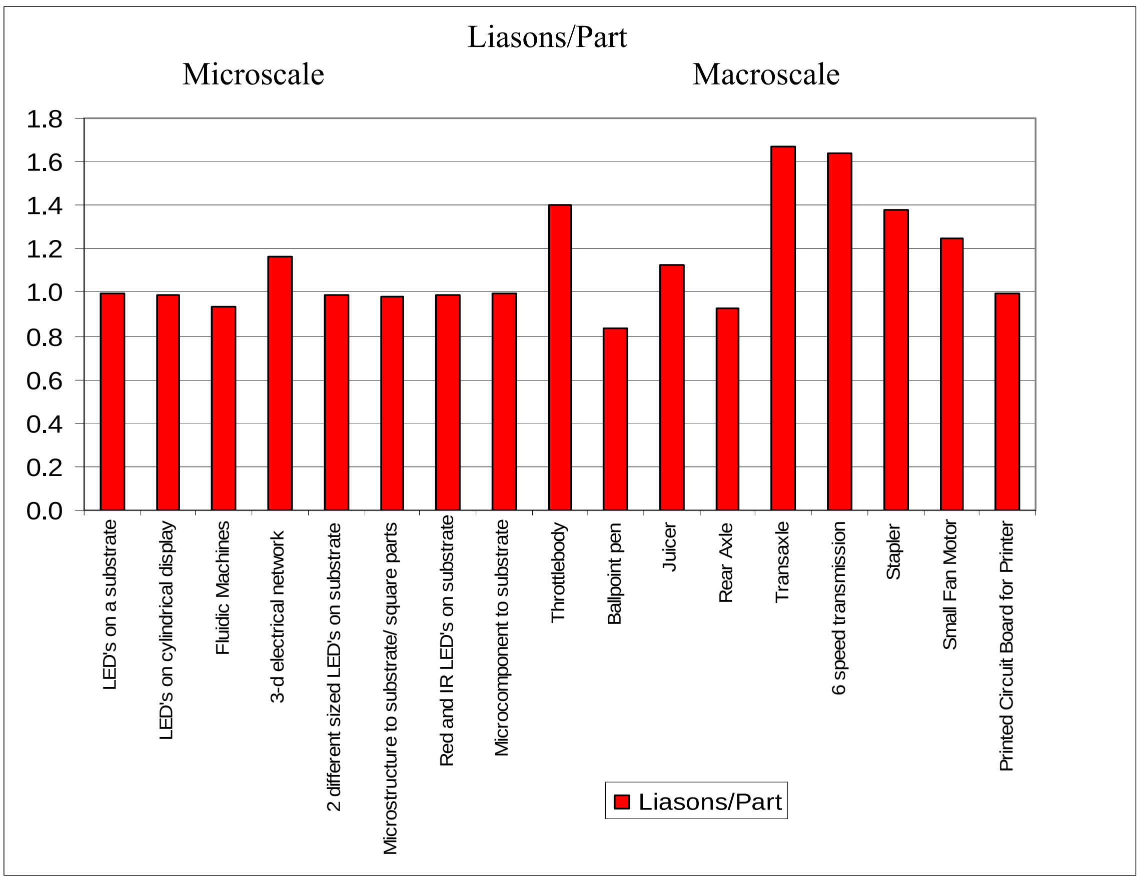


Figure 16- Liasons/ Part.

More liasons mean more toleranced interfaces, more complexity, more cost, and more places where failure can occur. This is why both assembly size scales are near the value of 1 and none are above 1.8. Most assemblies are exactly constrained or have one operating degree of freedom.

Figure 17 shows all of the criteria represented in a single graph to show the major differences between micro self assembly and macro assembly.

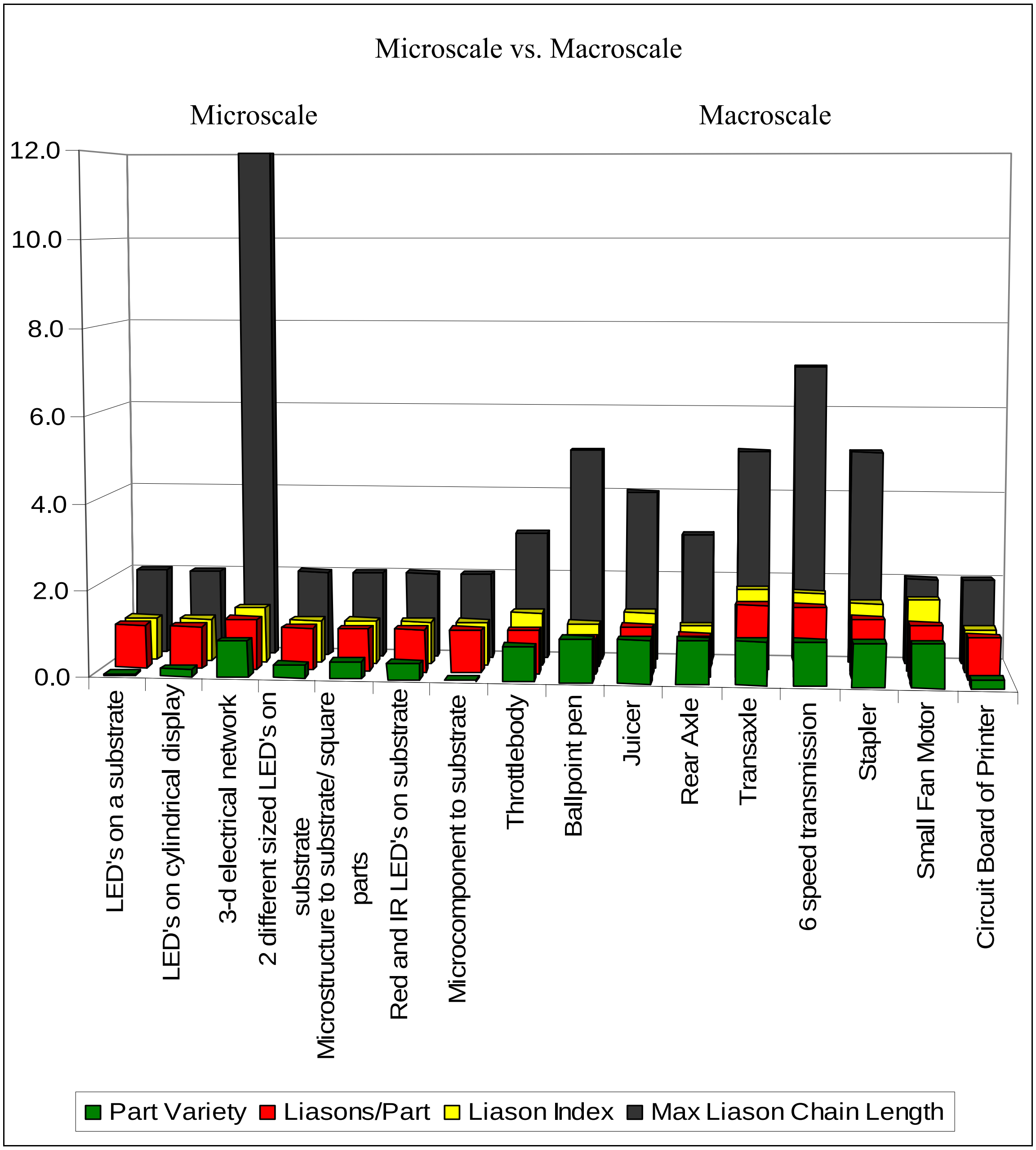


Figure 17- Micro Self Assembly vs. Macro Assembly.

From this data, it is shown that the part variety and maximum chain length are significantly different in the macro scale and in the micro scale. The part variety is different because the all of the parts in the macro scale are usually unique parts, with some parts being duplicated if the assembly is symmetric. The macro assembly process is serial, meaning that the assembly takes place in sequential order. However, in the micro scale, the parts are mainly the same part being assembled onto a substrate. The micro assembly process is parallel, meaning that the assembly of parts takes place all at once, thus limiting the part variety of the assembly. This can be overcome by combining the serial process of macro assembly into the parallel process of micro assembly, which would allow for more part variety to be achieved in the micro scale.

The max liason chain length is also different because of the assembly process in the macro scale and micro scale, which are serial process and parallel process. In the micro scale self assemblies where parts are being assembled to a substrate, only one layer of parts are being assembled so the maximum chain length that can be achieved is only two. In the macro scale, the max liason chain length can be an infinite value depending on how large the assembly is. Because of the parallel process in micro self assembly, the complexity of assemblies is limited.

Chapter 3- Self Assembly Concepts and Complex Self Assembly Structure

This thesis shows the differences in assembly at the macro and micro scales. Micro scale assembly is harder to achieve with high precision because of the size of the parts being used. Micro self assembly is presented to help overcome the problem. This chapter outlines requirements for self assembly that need to be achieved in order for micro assembly to have more complexity in the assemblies. The requirements are tested and a complex model structure is assembled using self assembly.

3.1 Self Assembly Requirements

In order for successful and complex self assembly to occur, certain requirements have been identified that must be met. These requirements were developed by looking at how assembly is accomplished in the macro scale. Parts in the macro scale most be assembled in a certain order for the final product to function correctly. This can be done in the micro scale by using controllable binding sites which allow for sequence of assembly. Templates or fixtures are used in the macro scale to assemble large or heavy parts and to help with the alignment of parts relative to each other. Without the fixtures in the macro scale, assembly of large parts would not be plausible. A tool substrate in the micro scale acts as a template or a fixture. At the macro-scale many potential errors are detected and corrected without scrapping the entire assembly. Being able to correct miss assembled parts on the fly would reduce waste and time, which can be done in the micro scale by designing parts and binding sites correctly. The developed requirements for micro scale self assembly are:

1. *Controllable Binding Sites* - Controllable binding sites are necessary because it allows for control in the order parts are assembled. Certain binding sites can be activated to assemble unique parts while other binding sites are disabled. This allows parts to be assembled in a sequential order.
2. *Angular Orientation Control* - Angular orientation is essential because most parts in assemblies must have the correct orientation relative to the other parts to operate correctly, however, some parts can have any orientation because they have a symmetrical structure.
3. *Reusable Tool Substrate* - A reusable tool substrate is needed so parts can be first assembled to the tool and then transferred to another final substrate, which allows for multiple layers of parts to be assembled. This allows for more complex assemblies to occur.
4. *Assembly Error Prevention & Correction* - Assembly error prevention and correction is required to save time and money in assembly. If the parts and binding sites are designed correctly, there should not be any error in assembly; however this is not always possible. The design should only allow for one part to attach to a binding site which can be achieved by spacing out the binding sites.

3.2 Experimental Implementation Methods

A goal of this thesis is to integrate these self assembly requirements. This work demonstrates for the first time the ability to incorporate all of these functions in a flexible system capable of doing complex self assemblies. The requirements are further discussed below to demonstrate the importance of each requirement. A feasible demonstration is also presented later on in this chapter.

3.2.1 Controllable Binding Sites

The ability to select where parts are going to assemble allows for more control of assembly. This can be done by selectively masking certain binding sites. An automated system could be implemented to mask the binding sites. The automated system would be a multi degree of freedom system that would allow for deposition and removal of the masking agent like an ink jet printer. The masking agent could be paint, a marker, or other liquids that aren't soluble in water. The masking in this work has been done by masking tape and permanent marker as a proof of concept which allows different part types to be assembled to one substrate. Controllable binding sites can also be accomplished by turning on and off certain binding sites using electrical connections. Electrical connections would add more complexity and cost to the assembly. Chung accomplished this by placing heaters that melted solder blocks on the substrate which allowed for precise placement of parts in the assembly (Chung et al. 457-464). Magnets are another option that could be used to control binding sites with the polarity of the magnets. The controlling of binding sites allows for more complex assemblies to occur.

3.2.2 Angular Orientation Control

Control of angular orientation is important in assembly because of tolerances and errors in assembly. Incorrect angular orientation will have an adverse affect on the final assembly. Angular orientation is critical because most parts in an assembly are not axially symmetric meaning the object could be rotated about an axis at any arbitrary angle and it would look the same. If the parts don't orient properly, they will not perform their desired function and may impede the assembly of more complicated or subsequent parts rendering the whole assembly useless. Angular orientation can be controlled by alignment pedestals (Zheng and Jacobs 1387) that allow only the correct sized part and angular orientation to be assembled.

Another way to control angular orientation is in the design of the binding site. If the contact pad is circular, the part can have any angular orientation, thus allowing error in assembly to occur. A square, triangle, or rectangle shape binding site will only allow the part to assemble in 4, 3, or 2 angular orientations respectively.

This work uses three circular contact pads in the binding site to control angular orientation shown in Figure 20. The parts and substrate have the same design. The use of more than one contact pad in the binding site solves the angular orientation problem but presents the problem of multiple parts sticking to one binding site which is discussed later.

3.2.3 Reusable Tool Substrate

A tool substrate that allows for transfer to a final assembly substrate is also helpful in creating complex self assemblies. The tool substrate allows for multiple part types to be assembled on multiple layers to establish a complex assembly. Macro assembly has the same capability by using fixtures and templates for assembly. This is helpful because the design would only need to be done for a generic tool substrate that can be used for many applications and different assembly structures.

A useful tool substrate should have these characteristics. First, the tool substrate should have reversible bonds. This allows for successful transfer to other substrates or layers of assembly. This thesis demonstrates this by using solder to assemble parts to a tool substrate which can be reversed. Second, the tool should be generic so different part types can be assembled. The tool substrate used was created with discrete bonding locations which parts bond to when solder is applied as shown in Figure 18. Finally the tool substrate needs to be reusable and durable. A one time use tool substrate would not be effective if multiple layers are being assembled.

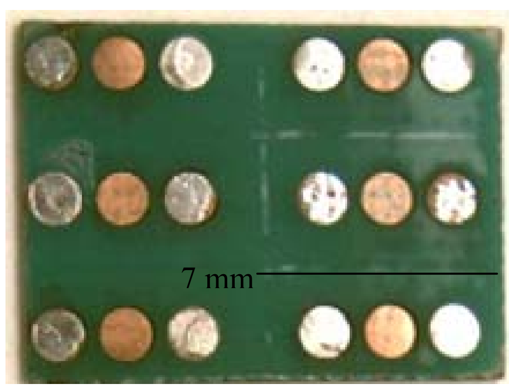


Figure 18- The Tool Substrate Used in This Thesis Which Consists of Six Parts.

3.2.4 Assembly Error Prevention and Correction

Being able to correct assembly errors during assembly is highly sought after. In self assembly, this can be realized by designing the parts and substrates correctly. The design of the parts and substrate should be designed so that only one part can assemble to the binding site. This work reduces error in assembly by eliminating the middle contact pad on the binding site. In solder based self assembly, incorrectly assembled parts can be disassembled by stronger agitation if the surface energy is low enough between the part and substrate, which improves the yield of assembly. The parts in self assembly are brought to the substrate until a bond is formed that is stronger than the agitation being used. Each contact is analogous to rolling a ball across a landscape as in Figure 19. If the velocity (initial energy) is too high, the ball will fly off the surface. Figure 19(a) has only one stable location, but Figure 19(b) has multiple stable positions.

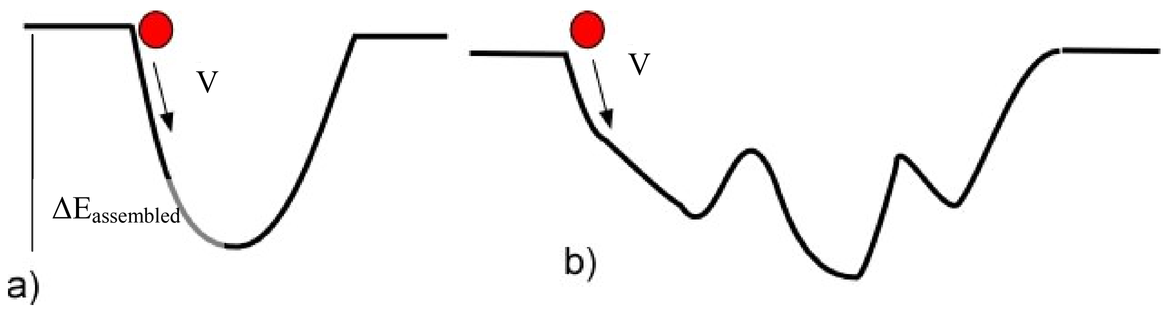


Figure 19- Balls Rolling Across the Terrain Illustrate the Self Assembly Process. In the ideal case (a), it is easy to know where the ball will stop, but many situations are not ideal (b). In (b), the initial velocity and height must be known to predict where the ball will stop.

Self assembly bonds can be designed to reduce the number of local minimum points, but often a multiplicity of minimum parts can not be entirely eliminated. However, if the arrival energy of the components and the magnitude of any disturbances can be tuned, successful assembly is possible. Generally, there will be both upper and lower bounds on the desired range of these disturbances so that the magnitude of the agitation (disturbance) energy ($E_{agitation}$), the energy ($E_{assembled}$) to remove properly bound parts, the energy and force to remove misassembled components ($E_{mis\text{-}assembled}$) should satisfy the inequalities:

$$\Delta E_{assembled} > \Delta E_{agitation} > \Delta E_{mis-assembled}$$

3.3 Basic Self Assembly Components and Methods

Solder based self assembly is presented in this work using printed circuit boards (PCB) produced by commercial vendors. Millimeter scale parts are cut from the boards for self assembly demonstrations. The substrates were various sizes, large parts were of size 3 mm by 7 mm and small parts were 3 mm by 3 mm. Figure 20 shows the PCB's used and the size of the three contact pad parts. The substrate part of the PCB was designed to disallow a part bond to more than one binding site. One binding site is defined by the three contact pads as shown in Figure 20. The binding sites are strategically placed so that a large part cannot assemble to two binding sites. The spaces between the binding sites are greater than the length of the large parts.

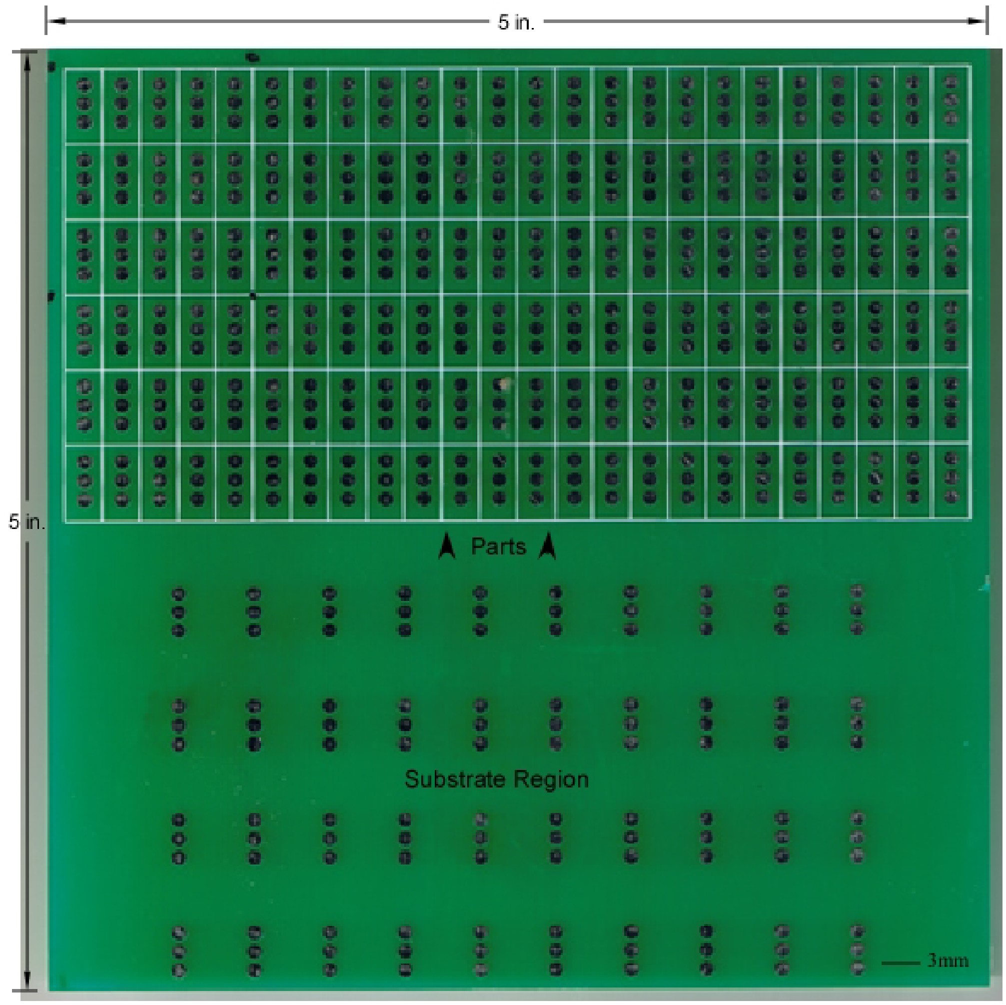


Figure 20- The PCB Board Used in This Thesis. The upper portion is the parts. The lower portion is the substrate area

The PCB was glued to a wood substrate and cut into pieces with a CNC mill in order to form the other test geometries illustrated in Figure 21.

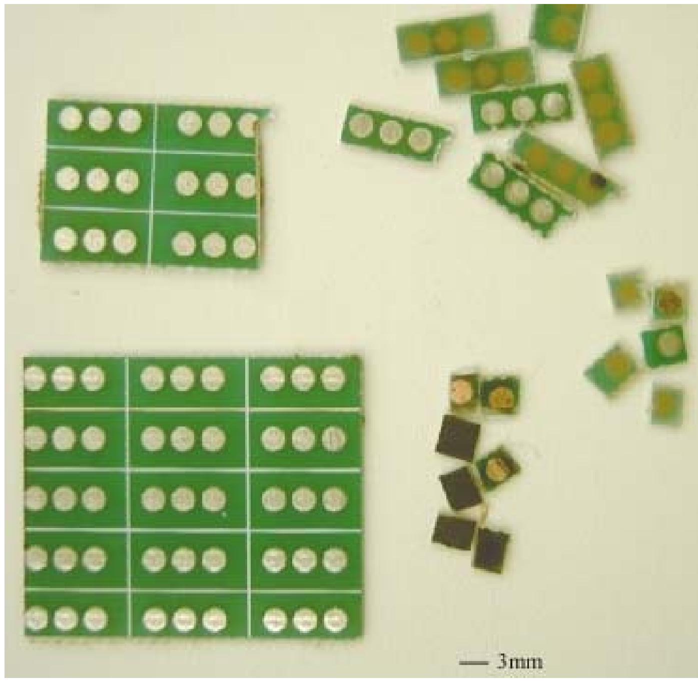


Figure 21- The Large Parts, the Small Parts, and the Substrates Used in Tests.

The self-assembly bonding locations were defined by bond pads on the PCB. The self-assembly solder did not bond well to the solder coating supplied by the manufacturer. To improve the self-assembly process, the solder was sanded off after the initial tests to expose the copper beneath. The low melting point (LMP) solder from Small Parts Inc. has a melting point of 47°C and composed of bismuth and other alloys.

3.4 Basic Self-Assembly Demonstration

The first test was done to show the concept of self assembly. A substrate was cut with 16 binding sites. The basic process, shown in Figure 22, was done as described below. First, the PCB board was attached to a wood substrate using super glue and then cut on the CNC mill. The parts were removed from the machining wood substrate by dipping them into acetone to remove adhesive and cleaned with acetone and hot water as well. Second, the substrate was attached to the bottom of a beaker with double sided Scotch tape. This allows the substrate to be stationary while the parts are in motion. Third, acidic water with a pH value of 2-3 was added to beaker and heated on a hot plate to 60°C to bring the solder to a molten state. The acidic water reduces the oxidation of the solder to maintain a clean surface that can bond with the copper substrates. The solder was applied to the substrate using a pipette. This was done by adding a solder droplet on the contact pads and removing the excess solder until a thin film was achieved. Fourth, the parts are added to the beaker and manual agitation is used to mix and assemble the parts.

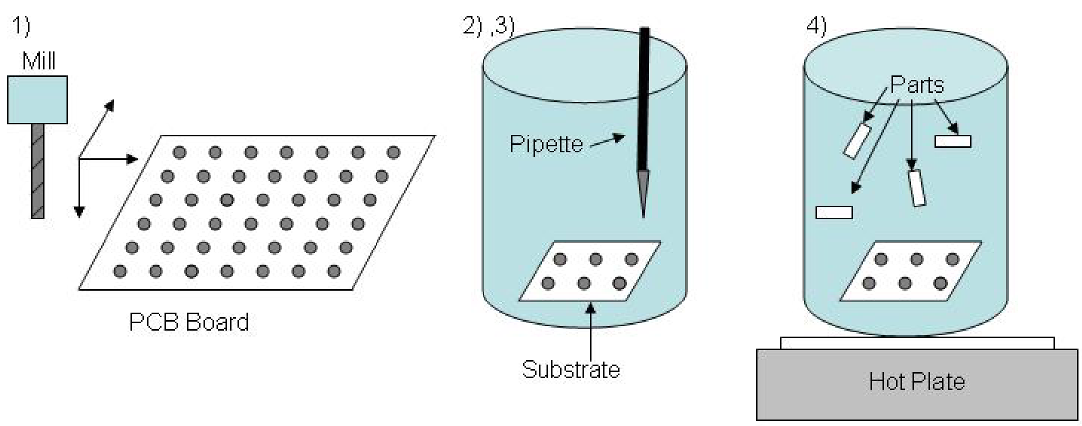


Figure 22- Self Assembly Process. 1) PCB board parts and substrates are cut out using CNC mill. 2) Substrate was taped to bottom of beaker. 3) Water is heated to 60 C and solder is applied to binding sites with pipette. 4) Parts are added to beaker and manual stirring is applied to assemble parts.

Finally, once the parts have assembled onto the substrate, the beaker is taken off of the hot plate. As the solution cools, the solder bonds solidify. This same process was used in subsequent demonstrations discussed in this chapter.

Solder was only applied to 8 of the 16 binding sites as shown in Figure 23 (black circles added to picture to show where solder was not applied). Only 16 parts were used for the first assembly test.

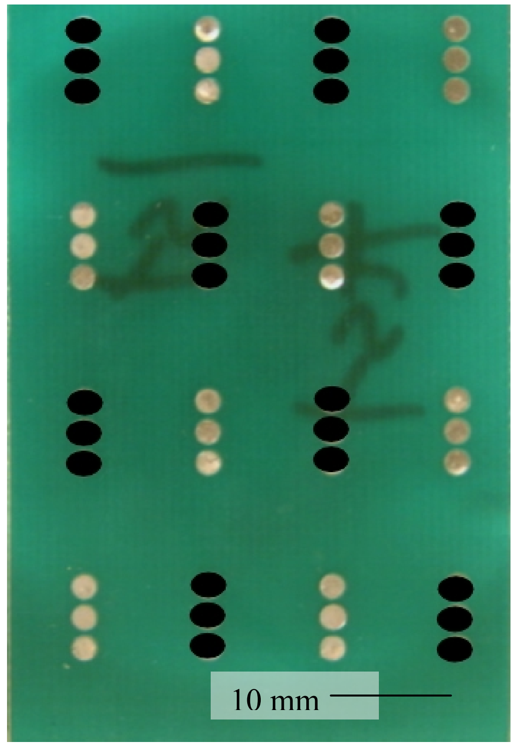


Figure 23- Substrate Used for First Self Assembly Test. Black areas show where no solder was applied.

Figure 24 shows the final assembled parts of the first test. Only 5 of the 8 binding sites have parts assembled to them seen in Figure 24. This occurred because the solder was applied inconsistently. Bond locations with large amounts of low melting point (LMP) solder did not bond as successfully as those with less LMP solder. Excess solder caused the parts to bounce off of the solder because the energy was too low for assembly to occur. On some of the binding sites, the solder was higher on one contact pad than the other, so the part would swivel on the high solder spot and not attach to the lower height solder. More parts in the liquid medium could have helped with having complete assembly occur. This problem was solved by applying a thinner film of solder.

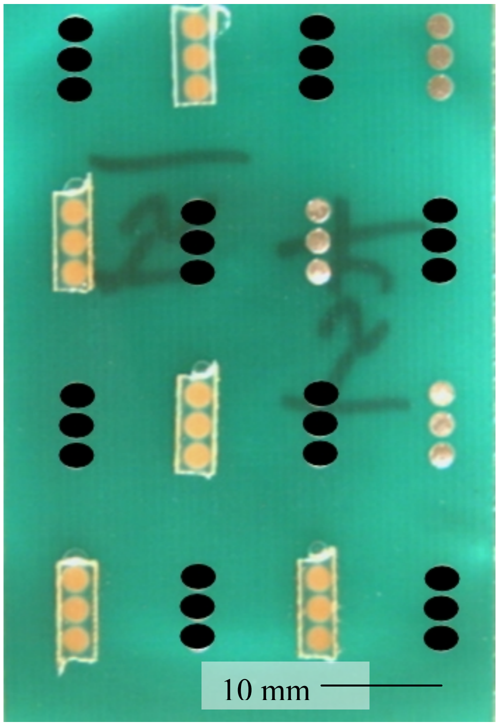


Figure 24- A Photograph Showing the Assembly of Parts Onto Substrate. Five out of eight parts assembled.

3.5 Binding Site Control and Assembly Error Correction

The second test shows the controllable binding sites concept by using tape to mask the binding sites where assembly is not wanted for certain assembly step. Another method, which uses a permanent marker, is demonstrated later in the multilayer assembly that is amenable to automation. This second test also shows the concept of error correction. The two part types being used are the same dimensions but have different colors (green and black). This is valuable since it allows for flexibility in design because many components (electronic chips, resistors, etc.) can have different functionalities but the same external geometry and structure. Figure 25 displays the initial substrate with certain binding sites covered.

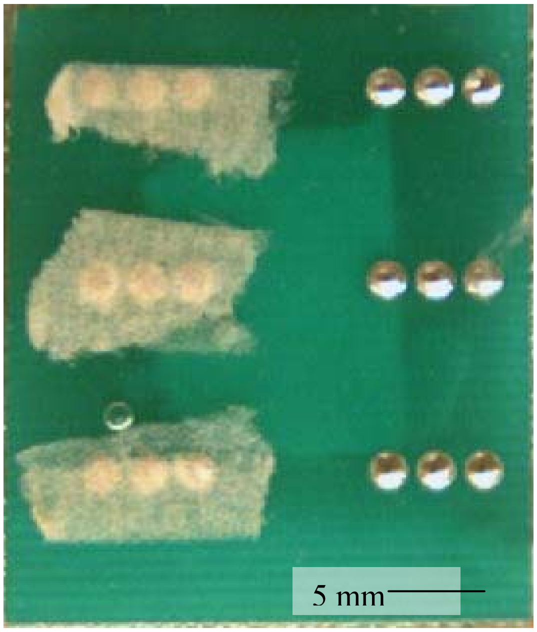


Figure 25- A Photograph of the Initial Substrate with Left Binding Sites Covered. This allows for different part types to assemble.

The green parts were chosen to assemble first. This was done by putting only green parts in the beaker first. After the green parts had assembled, the tape was removed along with the extra green parts, and the mixture containing only black parts are assembled in the same manner as the green parts. Figure 26 and Figure 27 show the assembly of the green parts and the black parts respectively. The figures show that for both part types, two parts are connected to one binding site which is not correct.

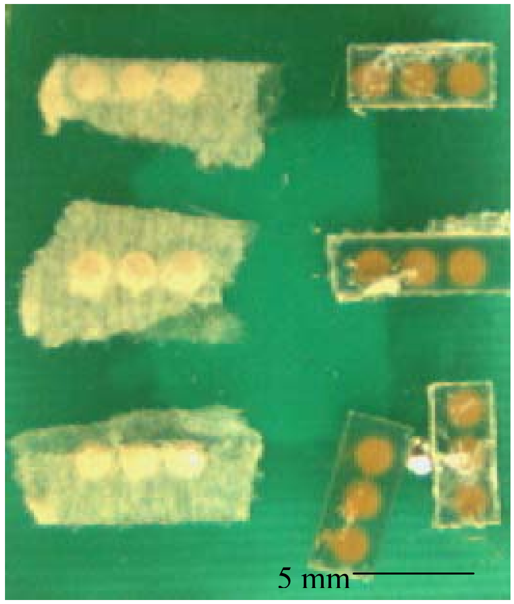


Figure 26- A Photograph Showing the Assembly of Green Parts. An error in assembly is shown in the lower right binding site.

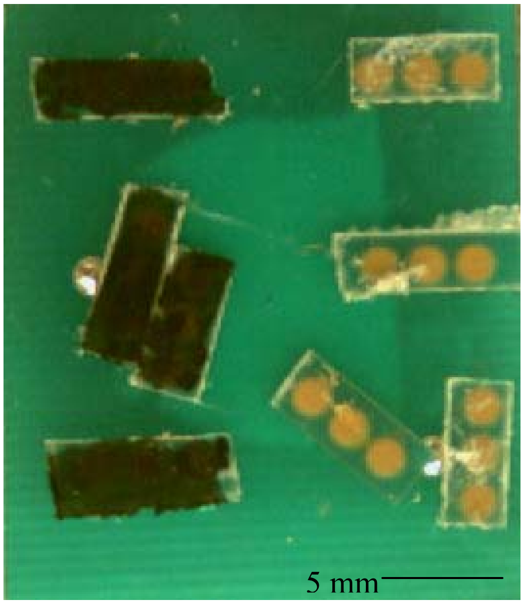


Figure 27- A Photograph Showing the Assembly of Black Parts. An error in assembly of the black parts occurred in the middle left binding site.

To correct the error in assembly, the substrate was detached from the bottom of the beaker and attached to a rod. When the substrate was hit against the side of the beaker, the parts that only had one contact pad assembling the part fell off. This occurs because the surface energy is not great enough to hold the parts on the binding sites when they are assembled incorrectly. Figure 28 proves this concept showing the misassembled parts removed from substrate. Once the misassembled parts are gone, assembly can be repeated until the parts are correctly situated. Solder does not have to be reapplied to the binding sites so the process is more effective with reputation.

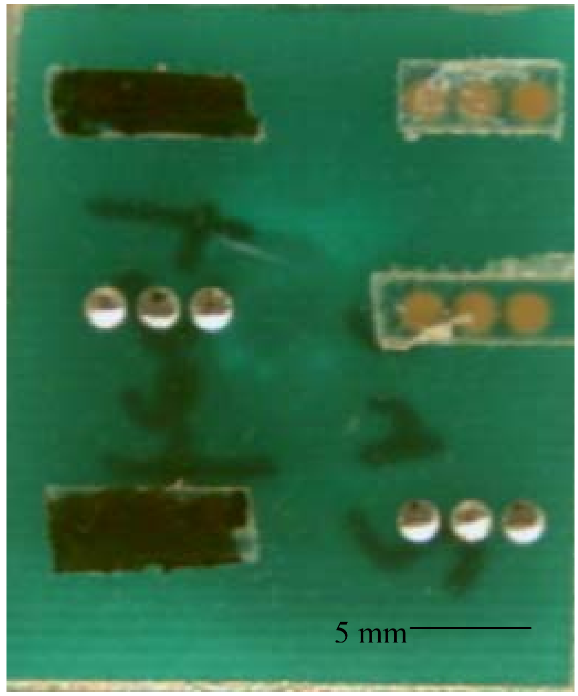


Figure 28 Substrate After Misassembled Parts are Removed.

3.6 Error Prevention by Contact Design

The third test of self assembly demonstrates the importance of substrate and part design. As seen in the second test, parts can assemble in a number of different ways, most of which are not wanted. Three, two, or one part can assemble to any given binding site. The closeness of the contact pads on the substrate allow for this to happen. Figure 29 shows possible different cases of assembly.

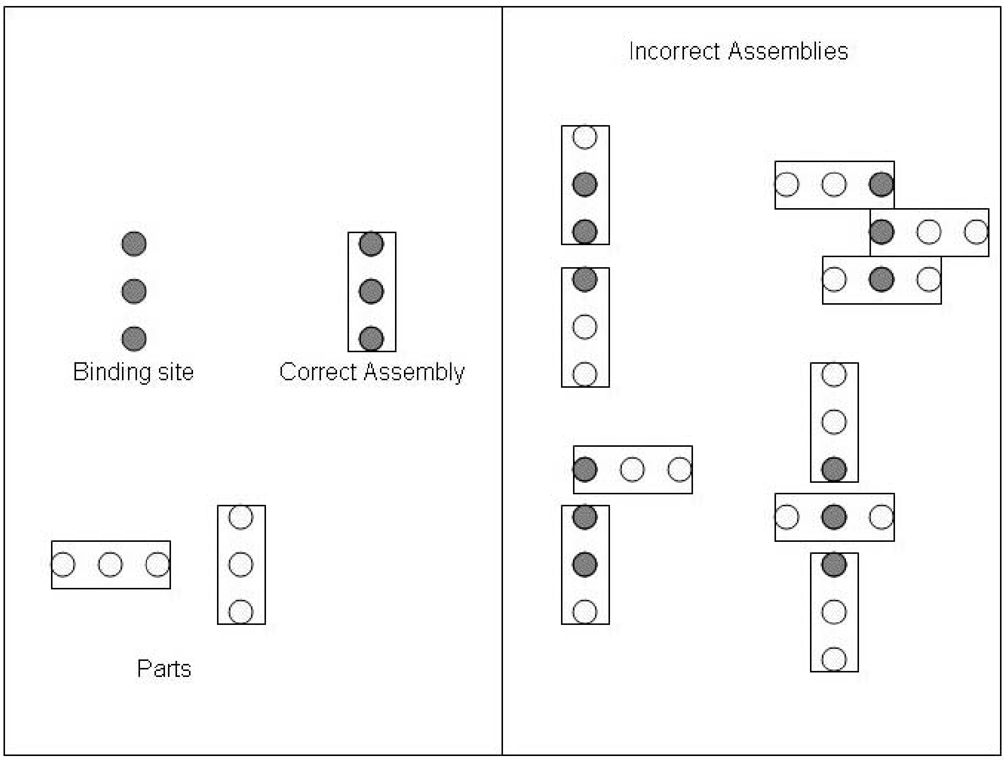


Figure 29- Possible Assembly Errors. Shows correct assembly on left and 4 incorrect assemblies on right.

The difference between the second test and the third test is the removal of LMP solder from the middle contact pad on both the binding site and the part. This reduces the error of having more than one part assemble to a binding site and having the middle contact pad of the part attach to a binding site. With the middle contact pad removed, there are only two possibilities of assembly: correctly assembled and two parts assembled on one binding site. Figure 30 illustrates these possibilities.

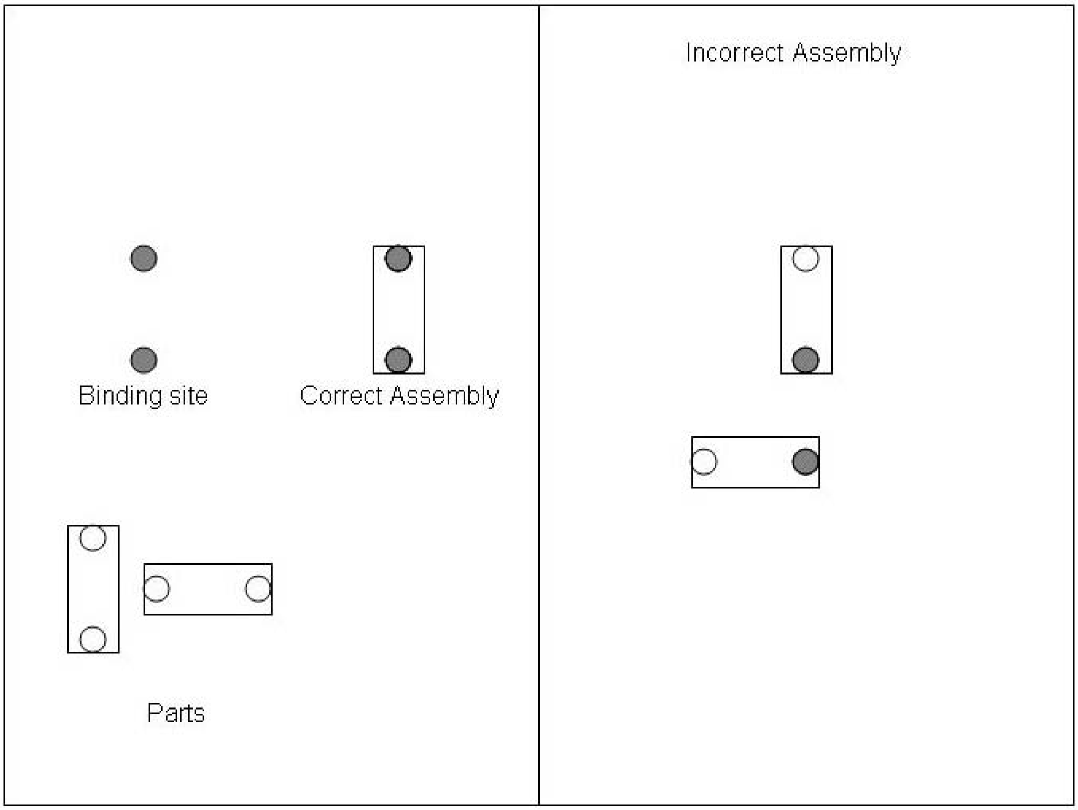


Figure 30- Assembly Possibilities with Middle Pad Removed from Part and Binding sites.

The initial substrate for this test is shown in Figure 31 with certain binding sites masked.

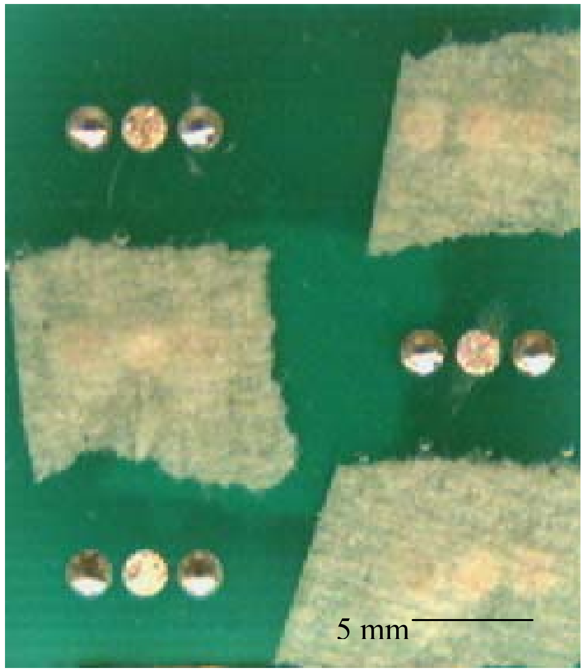


Figure 31 – Initial Substrate with Middle Contact Pads Removed on Binding Sites.

Assembly time was much quicker in test three than in test two because the misassembled parts did not have to be removed and misassembly did not occur. Figure 32 shows the assembly of green parts while Figure 33 shows final assembly. The error in Figure 32 which a green part assembled to only one contact pad was corrected when the black parts were introduced. The green part assembled to the other contact pad and assembly was completed.

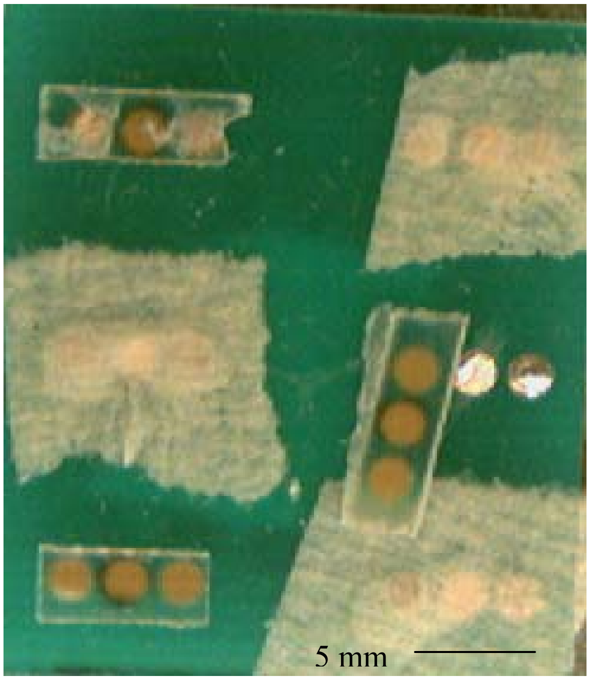


Figure 32- A Photograph Showing the Green Parts Assembled. The middle of the three binding sites was disabled. An alignment error occurred in the middle right binding site.

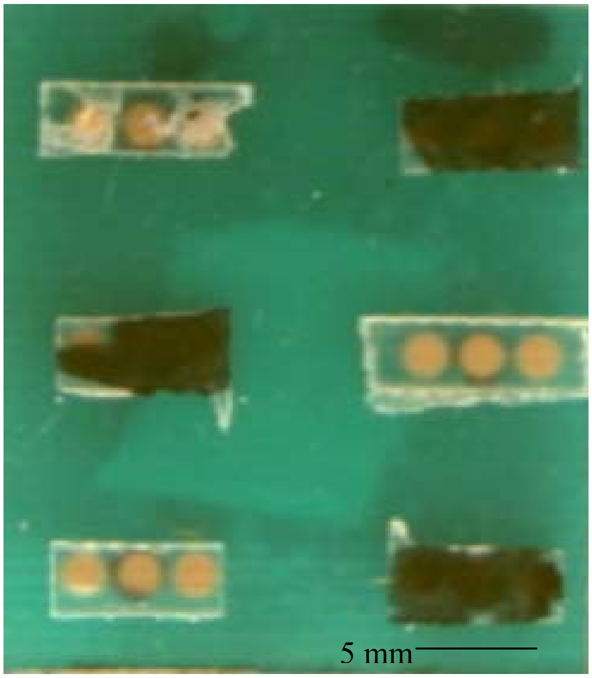


Figure 33- A Photograph of the Final Assembly State in Which Both the Black Parts Assembled and the Green Parts Assembled. Note that the green part self corrected the alignment error shown in Figure 32

3.7 Multi Part and Multi Layer Self Assembly

Complex structures have not been currently demonstrated in artificial self assembly like in natural self assembly (biology and chemistry). This was shown in Chapter 2 of this thesis. Most of the self assembly work is single layer and single part types. This test presents self assembly of a complex structure with multiple part types and multiple layers. Although the materials are different, the structure of the assembly is identical to the structure of a thermoelectric cooler as seen in Figure 34. A thermoelectric cooler needs to be an assembly because the individual parts that make up the assembly are different materials and have different functions. If the parts used to assemble a thermoelectric cooler were all the same material, the cooler would not function.

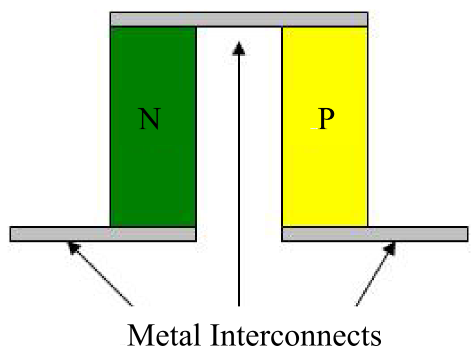


Figure 34- Structure of a Thermoelectric Module.

A thermoelectric cooler consists of two substrates (top and bottom), interconnects, and n-type and p-type parts. Thermoelectric coolers are solid state heat pumps that operate on the Peltier effect; the theory is that there is a heating or cooling effect when electric current passes through two conductors. A voltage is applied to the free ends of two dissimilar materials, which creates a temperature difference. With this temperature difference, Peltier cooling will cause heat to move from one end to the other. A typical thermoelectric cooler will consist of an array of p- and n- type semiconductor elements that act as the two dissimilar conductors. The array of elements is soldered between two ceramic plates, electrically in series and thermally in parallel. As a dc current passes through one or more pairs of elements from n- to p-, there is a decrease in temperature at the junction ("cold side") resulting in the absorption of heat from the environment. The heat is carried through the cooler by electron transport and released on the opposite ("hot side") as the electrons move from a high to low energy state. The heat pumping capacity of a cooler is proportional to the current and the number of pairs of n- and p- type elements (or couples). In this example, these parts are all simulated by the PCB components illustrated in Figure 21.

This test introduces the concept of a tool substrate to enable production of the more complicated multi-layer structure. Parts are assembled to the tool and then transferred to another substrate. As the process is repeated, multiple layers are assembled. The figures below show the process and pictures of the steps taken to achieve a complex structure through self assembly.

In Figure 35, the tool substrate is inserted into heated beaker and solder is applied to desired binding sites. The interconnects are then added to the beaker and manual agitation is used. Once parts have assembled, beaker is removed from the heat source.

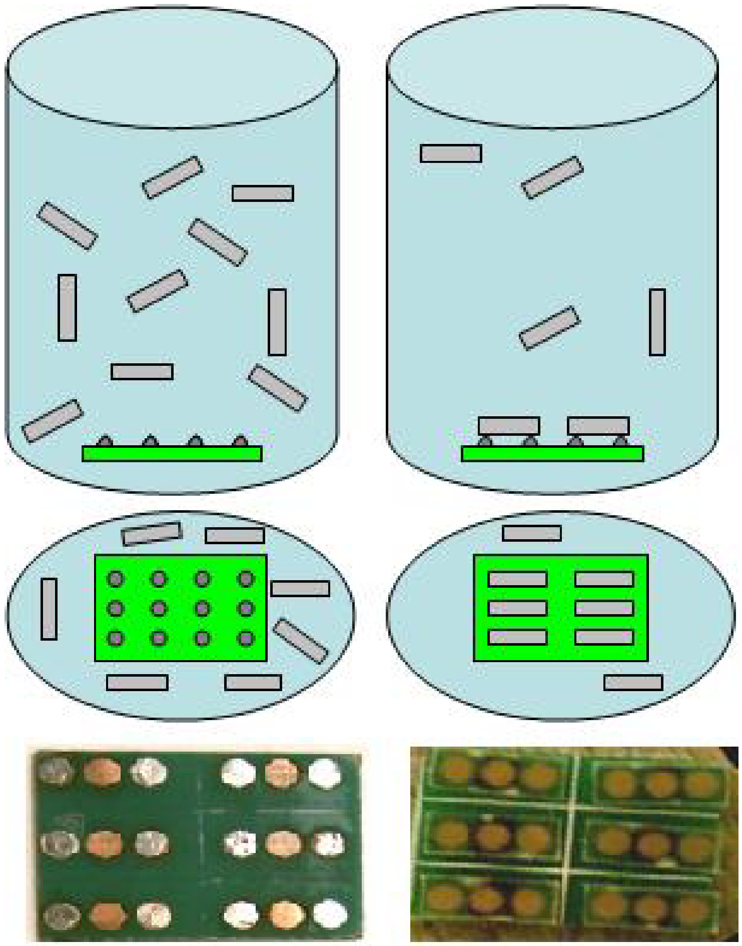


Figure 35- A Photograph of the First Step in Assembling a Complex Structure. Solder is applied to tool substrate in acidic water and heated. The interconnects are then added to a beaker and self assembly occurs. Left side shows initial tool substrate. Right side shows after assembly occurs.

After the solder has solidified, the tool substrate is removed from the beaker. The tool substrate is then glued to the final substrate using super glue. After the adhesive has dried, the assembly is placed back into the beaker and the solder is heated until molten. Once molten, the tool substrate is removed from assembly as shown in Figure 36.

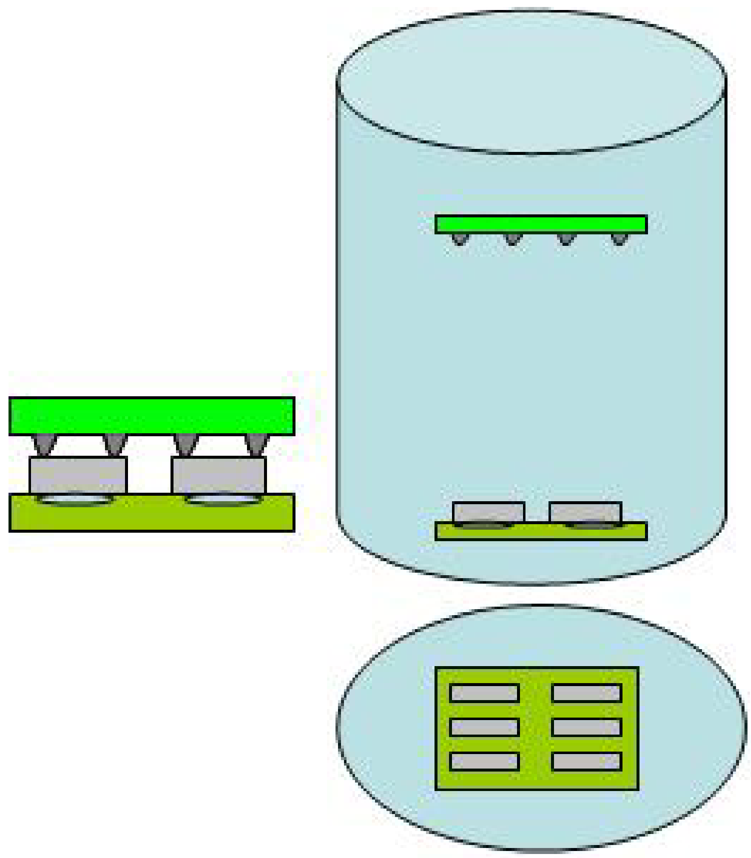


Figure 36- Parts Assembled to Tool Substrate are Attached to Final Substrate with Adhesive. Once adhesive dried, assembly was placed back in heated water to release the tool substrate.

The tool substrate is then placed back into the beaker. Solder is applied to the desired configuration and the green part (shown as black in physical picture) is assembled shown in Figure 37. After the green parts have fully assembled, the extra parts are removed from the beaker. The other binding sites are then coated with solder with assembly of the yellow parts (shown as green squares with yellow circles in the photograph) following.

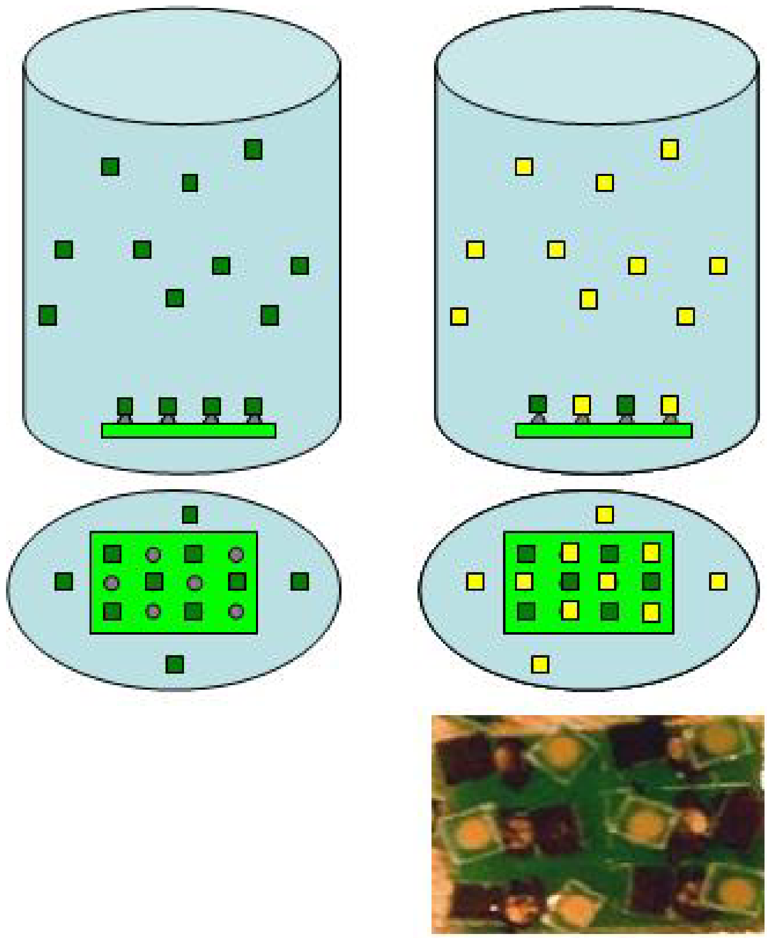


Figure 37- Tool Substrate is Used Again to Assemble the Two Different Part Types. Assembly is done by masking the desired pattern on the tool substrate with a marker.

After the green and yellow parts have been assembled to the tool substrate, the assembly is glued to the final assembly. After solder has become molten, tool substrate is removed as shown in Figure 38.

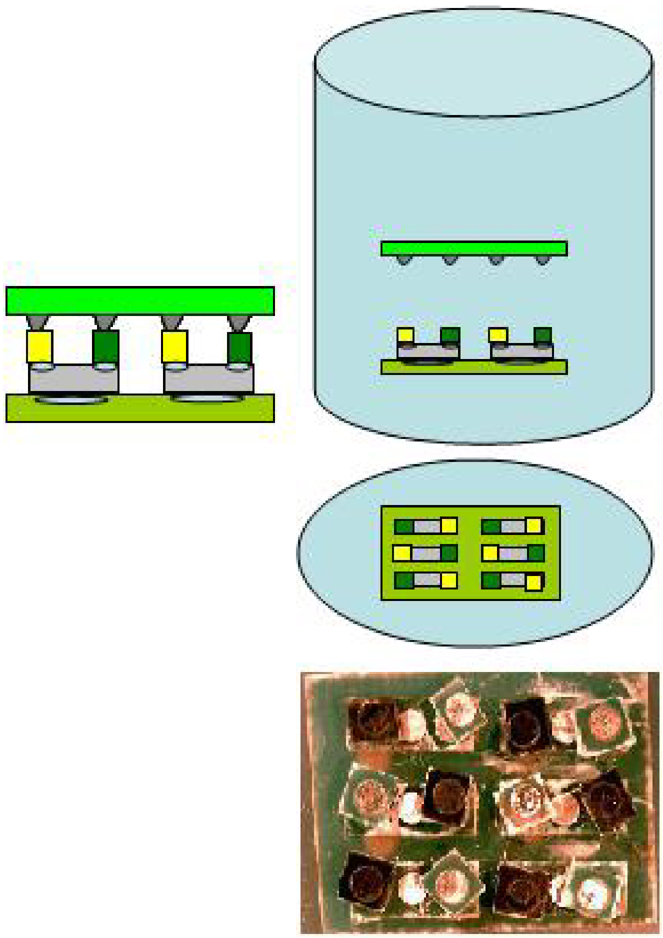


Figure 38- The Tool Substrate with the Two Different Part Types Assembled is Glued to the Final Substrate with Interconnects on it. The angular orientations of the single pad parts are not satisfactory. This occurred because of the circular contact pads.

Figure 39 shows the next step where interconnects are attached to the tool substrate. The tool substrate is placed back into the beaker, solder is applied where needed, and the interconnects are assembled. After the solder has solidified, the tool assembly is glued to the final assembly.

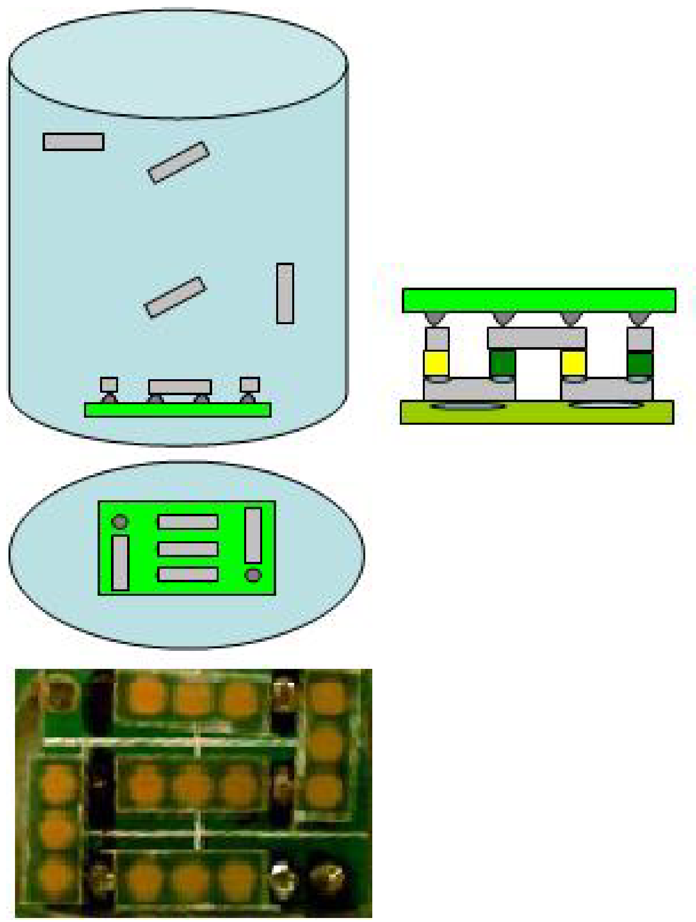


Figure 39- Another Layer of Interconnects are Attached to the Tool Substrate. The parts are again glued to the final assembly with adhesive.

Once the glue has dried, the assembly is placed back into beaker and tool substrate is removed once solder is molten. The assembly is then removed from beaker and is allowed to dry. Once the assembly is dry, a top substrate is added and the assembly is complete as shown in Figure 40.

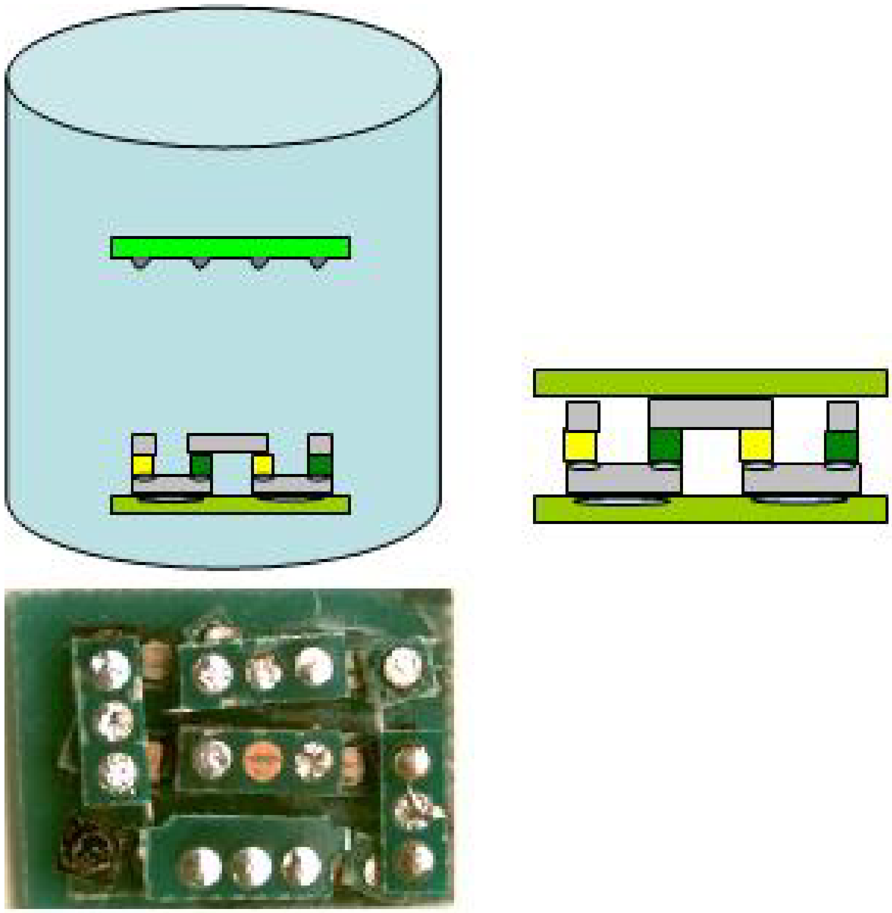


Figure 40- A Photograph of the Final Steps. Tool substrate after it is removed from the final substrate. Another substrate is positioned on top of other layers to complete assembly. A three layer structure is achieved.

The process described above shows that it is feasible to accomplish all of the self assembly requirements. A multi layer assembly with multiple part types is demonstrated above. The metrics in Chapter 2 to compare macro assembly and micro self assembly are calculated to show that this assembly process can create more complex assemblies than previously reported. A liaison diagram for the assembly is shown in Figure 41.

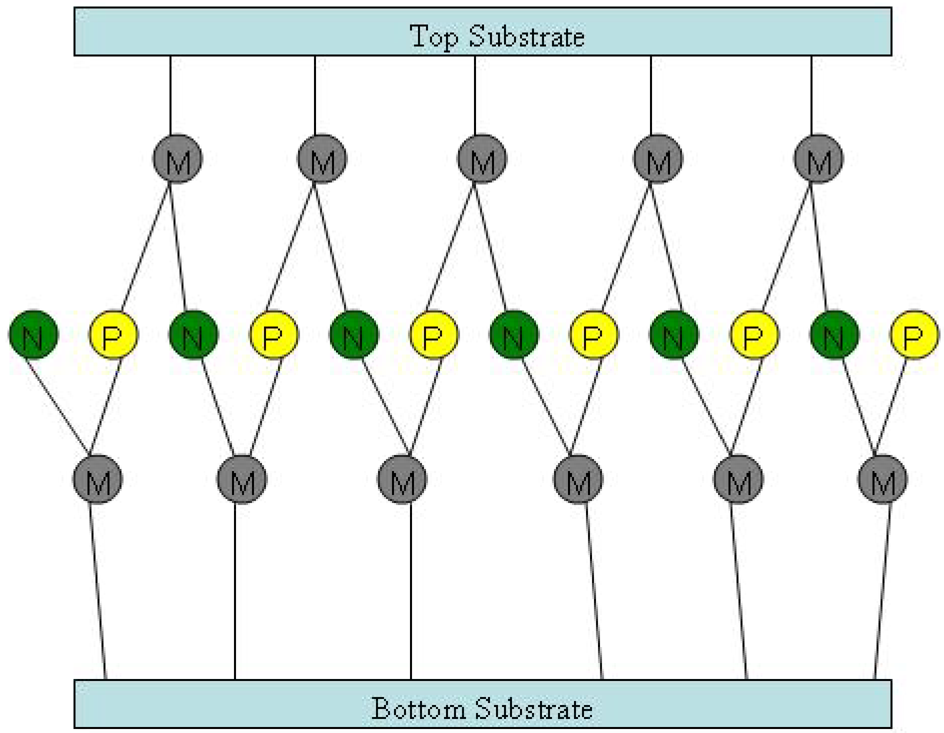


Figure 41- Liason Diagram of Multilayer Assembly. M represents the metal interconnects. N and P represent the two types of thermoelectric pieces.

This assembly has a total of 25 parts and 4 different part types, which gives a part variety of 0.160. The max liason chain length is 23, showing that the assembly has more than one layer. Values of 1.32 and 1.38 were calculated for liasons/part and the liason index respectively. These values are all higher than the current artificial self assemblies presented earlier in Chapter 2. Figure 42 shows this difference graphically.

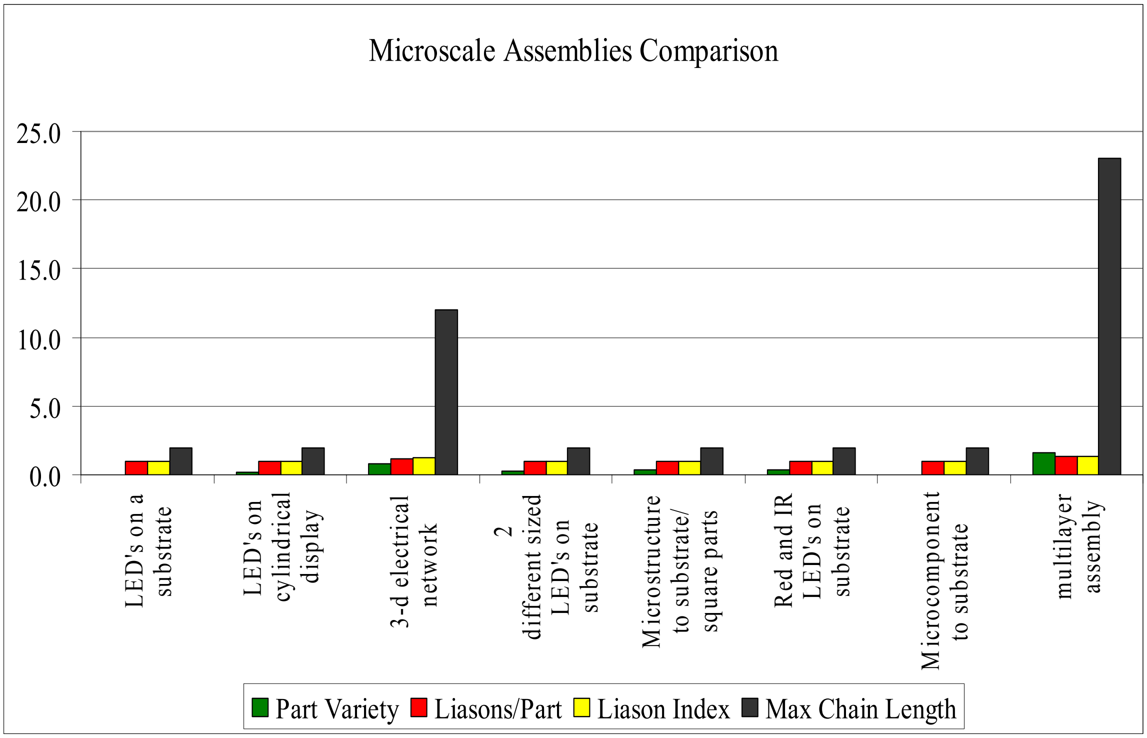


Figure 42- Graph Showing Multilayer Assembly vs. Previously Reported Microscale Self Assemblies. Part variety is scaled up ten times to show difference better.

This chapter has demonstrated the basic concepts of artificial self assembly and that a more complex assembly can be achieved using self assembly. The requirements for successful and more complex self assemblies were also developed and tested. The problem of orientation control seen in the multi layer assembly can be solved. To solve the angular orientation problem with the circular contact pads, square contact pads can be designed and manufactured to fix that problem. The square contact pads would orient the parts correctly and allow the assembly to have a solid structure.

Chapter 4- Conclusions and Recommendations

Macro assembly was used as a standard to compare and analyze current artificial micro self assembly. Liason diagrams and developed criteria (part variety, liasons/part, liason index, and max liason chain length) were employed to make the comparison between the two size scales. The comparison was instrumental in developing certain self assembly requirements that need to be met to show successful and complex self assembly, which has not currently been seen. A prototype self assembly method that can assemble complex structures is tested to show proof of concept.

4.1 Recommendations

4.1.1 Advancement of Prototype Assembly Method

A prototype self assembly method that incorporates binding site control, angular orientation control, a reusable tool substrate, and error prevention and correction was developed in this thesis. The structure of a thermoelectric cooler is demonstrated using printed circuit boards for the parts and substrate. The ability to self assemble a working thermoelectric cooler is being studied using the assembly method in this thesis. This would further help express the usefulness of self assembly in the micro scale and show that complex assemblies can be accomplished using self assembly.

Automation of solder deposition would greatly improve the accuracy and time of assembly. The solder deposition process described in the thesis is done by hand using a pipette. An excess amount of solder is first deposited on the binding sites. The excess solder is then removed from the binding site using the pipette to "suck up" the solder until a thin layer is left. This process was sufficient for the work done in the thesis, but would not be feasible in a commercial assembly application because of the inconsistent height of the solder being applied. Too much time would be wasted if the solder was applied to each binding site by hand. An automated system, like an ink jet printer, should be designed and tested so that the solder height is known and consistent for each binding site. This would be extremely helpful in commercial micro scale assemblies where a change in height of one part can cause the whole assembly to not function correctly.

4.1.2 Apply New Self Assembly Concept to Other Assemblies

The new self assembly concept presented should not be limited to only being used to assemble the structure of a thermoelectric cooler. This new assembly concept can be used to assemble parts where strong mechanical bonds, accomplished by the use of solder, are needed. It would also be helpful where assemblies have multiple layers. Self assembly can be used to assemble micro machines, digital displays, and other products that are designed for self assembly.

4.2 Conclusion

This thesis demonstrated that self assembly processes can produce new multilayer complex structures. The comparison between macro assembly and micro self assembly is very valuable in showing the complexity of the macro scale and where micro scale assembly can go in the future. Self assembly offers the promise of waste-free, cost-effective, high-volume production of complex structures with the possibility of error correction at any stage of assembly. This work has developed a new self assembly concept that has potential advantages over previous self assembly concepts. The new assembly concept incorporates concepts that were used individually in current self assembly. In particular, this work shows that the earlier self assembly concepts can be unified into an effective self assembly process.

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Appendices

Appendix A: Data Used for Macro and Micro Comparison

The following tables show the data used to generate the graphs in Chapter 2 which allows for the comparison between the macro and micro scale. Tables 5 and 6 represent the micro scale assemblies.

Table 5- Data Used for Microscale.

Author	Micro Papers	No. Part Types	No. of Parts	No. of Liasons	Liasons/ Part
Zheng	LED's on a substrate	2	601	600	1.00
Jacobs	LED's on cylindrical display	2	113	112	0.99
Gracias	3-d electrical network	1	12	14	1.17
Zheng	2 different sized LED's on substrate	3	101	100	0.99
Srinvisan	Microstructure to substrate/ square parts	2	50	49	0.98
Singh	Red and IR LED's on substrate	3	81	80	0.99
Fang	Microcomponent to substrate	2	1001	1000	1.00
Nellis	multilayer assembly	4	25	33	1.32

Table 6- Criteria Data for Microscale.

Author	Micro Papers	Min/ Part	Liason Index= (Liason/part)/ (min/part)	Max Liason Chain Length	Part Variety
Zheng	LED's on a substrate	0.998	1.00	2	0.033
Jacobs	LED's on cylindrical display	0.991	1.00	2	0.177
Gracias	3-d electrical network	0.917	1.27	12	0.833
Zheng	2 different sized LED's on substrate	0.990	1.00	2	0.297
Srinvisan	Microstructure to substrate/ square parts	0.980	1.00	2	0.400
Singh	Red and IR LED's on substrate	0.988	1.00	2	0.370
Fang	Microcomponent to substrate	0.999	1.00	2	0.020
Nellis	multilayer assembly	0.960	1.38	23	1.600

Appendix A: (Continued)

Tables 7 and 8 represent the macroscale assemblies.

Table 7- Data Used for Macroscale.

Macro Comparisons	No. Part Types	No. of Parts	No. of Liasons	Liasons/ Part
Throttlebody	4	5	5	1.00
Ballpoint pen	6	6	5	0.83
Juicer	8	8	9	1.13
Rear Axle	13	13	12	0.92
Transaxle	9	9	15	1.67
6 speed transmission	11	11	18	1.64
Stapler	8	8	11	1.38
Small Fan Motor	4	4	5	1.25
Circuit Board of Printer	28	136	135	0.99

Table 8- Criteria Data for Macroscale.

Macro Comparisons	Min/Part	Liason Index= (Liason/part)/(min/part)	Max Liason Chain Length	Part Variety
Throttlebody	0.800	1.25	3	0.80
Ballpoint pen	0.833	1	5	1
Juicer	0.875	1.29	4	1
Rear Axle	0.923	1	3	1
Transaxle	0.889	1.88	5	1
6 speed transmission	0.909	1.80	7	1
Stapler	0.875	1.57	5	1
Small Fan Motor	0.750	1.67	2	1
Circuit Board of Printer	0.992	1	2	0.21